MOVEMENT

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BY

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TRANSLATOR'S NOTE

Instantaneous photography, especially that branch of it known as Chronophotography, has already won for itself a recognized position among the methods of scientific research, and in the near future it is probable that it will be even more generally appreciated. Marey and Muybridge must undoubtedly be regarded as the two pioneers of the method; the works of the latter, written in English and published in America, are within the reach of all who can read the English language; on the other hand, the works of Marey are for the most part inaccessible to those who are unfamiliar with French. It is for this reason that I applied for and obtained permission to translate this work.

"Le Mouvement" is one of the most recent and important publications of this eminent physicist and physiologist, and it is, I believe, the most comprehensive summary hitherto published, of the results and possibilities of instantaneous photography; every page has its interest not only for the specialist, but also for the general reader; and further, the book is replete with suggestiveness of new lines of research.

Chronophotography is a new subject, and many of

its technical terms are known even to English scientific men only in their French form. For these I have frequently used periphrases, remembering that many of my readers may not be experts. I must acknowledge gratefully the continued assistance of my sister, Mrs. Chalmers Mitchell, not only in making the actual translation, but in revising it for the press.

ERIC PRITCHARD.

14, Cromwell Place, S.W.,
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PREFACE

The graphic method, with its various developments, has been of immense service to almost every branch of science, and consequently many improvements have of late been effected. Laborious statistics have been replaced by diagrams in which the variations of a curve express in a most striking manner the several phases of a patiently observed phenomenon, and, further, a recording apparatus which works automatically can trace the curve of a physical or physiological event, which by reason of its slowness, its feebleness, or its rapidity, is otherwise inaccessible to observation. Sometimes, however, a curve which represents the phases of a phenomenon is found so misleading that another and more serviceable method, namely, that of chronophotography, has been invented. The development of these new methods of analyzing movement could never have proceeded within the confined space of a physiological laboratory. For instance, in comparing the locomotion of various species of animals, it is essential that each should be studied under natural conditions: fish in fresh water or marine aquariums; insects in the open air; and man, quadrupeds, and birds in wide spaces in which their movements are unfettered.

The Physiological Station, endowed by the State and the City of Paris, has afforded in this respect unique opportunities, and there, with new appliances, the following investigations have been for the most part carried out.

We shall see by a variety of instances to what extent the older methods are applicable for the analysis of certain phenomena, and what progress has been achieved by chronophotography.

Each chapter is nothing more than an outline, for any attempt to fill in the details of any section would monopolize the time and attention of a trained specialist.

In a few instances such an attempt has been made, for geometricians, hydraulic engineers, naval and military men as well as artists have all had recourse to this method, and at last naturalists have interested themselves in the matter. It is more especially to this latter class that we dedicate our work, since it appeals to their particular ambition, namely, that of discovering among the phenomena of life something that has hitherto escaped the most attentive observation.

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MOVEMENT

CHAPTER I

TIME

Its Graphic Record; Time-measurement by means of Photography

Summary.—Graphic record of time—Chronography—Rudiments of the method—Transmission of movement to the recording needle which registers the duration—Chronographic record of a man's foot in walking, during the phases of rest and motion—The same of the four feet of a horse in its various paces—Record of the fingering of a pianist—Applications of photography to the registration of time—Measurement of the exposure allowed by a photographic shutter—Measurement of the time intervals between successive exposures.

Graphic Record of Time.—Time, like other magnitudes, can be represented in a graphic form by straight lines of various lengths. In this way the respective duration of several events can be gauged by the various lengths of parallel straight lines placed side by side. The order of commencement of these phenomena can be expressed by the relative positions of the beginnings of the straight lines. With regard to the exact order and duration of the events, they can be indicated by means of a scale, subdivided into divisions which

represent years, days, or fractions of seconds. A diagram will elucidate this method of time-measure-

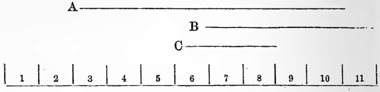

FIG. 1.—Scale of hours. Time measurement.

ment. Suppose we require to express the order and sequence of three events, A, B, C, which occur during a period of 11 hours. Their respective time relations are expressed most clearly by the three lines A, B, C, and by the scale of hours which accompanies them. It may be seen by a glance at the diagram that the event A commences at 2 o'clock and finishes at 10 o'clock (its total duration is, therefore, 8 hours); that B, commencing at 6 and ending at 11 o'clock, has lasted 5 hours; and that C, commencing at 5 o'clock and ending at a $\frac{1}{4}$ past 8, has only extended over a period of $3\frac{1}{4}$ hours. The sequence of these events is accurately expressed by the divisions on the scale, which correspond to the beginnings of the different lines.

Language is as slow and obscure a method of expressing the duration and sequence of events as the graphic method is lucid and easy to understand. As a matter of fact, it is the only natural mode of expressing such events; and, further, the information which this kind of record conveys is that which appeals to the eyes, usually the most reliable form in which it can be expressed. A celebrated English political economist, W. Playfair, has drawn up a table of the chronological order of the reigns of the various English sovereigns. From it one can see at a glance the age at which each succeeded to the throne, as well as the duration of the

reign. By the side of this chronological table, another series of lines shows the succession of the various ministers, and a third shows the periods of war and peace occurring during the respective epochs.

Such a table expresses in the most lucid manner the sequence of events. That such a mode of graphic record has been neglected in France cannot be too deeply deplored. A somewhat similar method was utilized in France during the last century to express the duration and sequence of certain acts. Vincent and Goiffon * have represented by a chronological record the phases of rest and motion of horses' feet, as observed in their different paces. This mode of expression is surely preferable to that of language, when it is a question of conveying to the mind the meaning of complicated rhythms.

Chronography.—The diagrams of which we have just been speaking are, however, only one mode of representation, clearer, it is true, than others, but reliable only in so far as the data on which they depend are trustworthy. In experiments, for instance, which deal with time measurements, it is of immense importance that the graphic record should be automatically registered, in fact, that the phenomenon should give on paper its own record of duration, and of the moment of production. This method, in the cases in which it is applicable, is almost perfect. In other instances photography comes to the rescue, and affords accurate measurements of time events which elude the naked eye. The process which thus serves to register the duration and sequence of events constitutes a method called "chronography."

We are about to explain this method, proceeding

* Mémoire artificielle des principes relatifs à la fidèle représentation des animaux tant en peinture qu'en sculpture, par feu Goiffon et M. Vincent. In-fol. 1779.

from the more simple to the more complicated cases. We shall first show how the method can be applied to register the successive phases of rest and motion, as executed by a man's foot in walking, and then the movements of the four feet of a horse as they occur in its various paces, and, lastly, the automatic method of registering the fingering of a pianist on the keys of his instrument. This last problem must be regarded as one of the most difficult to solve.

Rudiments of Chronography.—Let us suppose that a strip of paper is made to travel by clockwork at a uniform rate, and that a pen fixed above the paper marks, as it alternately rises and falls, the various periods and intervals.

As the pen comes in contact with the paper it leaves its record in the form of "dashes," of various lengths, and at various intervals; and by this means the sequence and duration are registered. If the "dashes" are equidistant, it means that the periods of contact follow one another at equal intervals of time. Finally, if it is necessary to obtain an accurate measurement of the duration of contact, and of the intervals between, the exact rate at which the strip of paper is being carried must be known. A control record of the rate may be obtained by allowing the oscillation of a pendulum to mark the seconds on the paper, or, if the movement be very rapid, by allowing the vibrations of a tuning-fork, of which the rate of vibration is known, to trace themselves upon the paper.*

Transmission of the Movement to the Recording Needle which registers the Duration.—It hardly ever happens that the phenomena, of which one wishes to record the sequence and duration, are capable of acting directly on the recording needle. More often such

* For the general principles of chronography, its technique and applications, see "The Graphic Method," pages 133, 142, 456.

movements have to be observed at a distance and transmitted to the corresponding recording needle. For this purpose transmission by air is employed and found preferable to transmission by electricity. The following apparatus effects this object.

Two similar apparatuses are coupled together by pneumatic connecting tubes, and the whole apparatus goes by the name of "lever-drums."* Each part con-

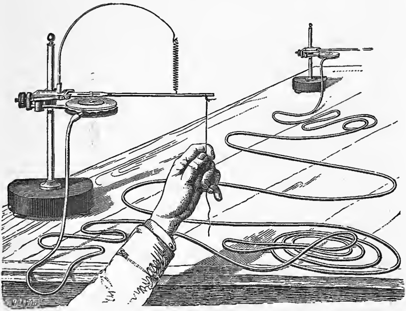

FIG. 2.—Arrangement designed for transmitting a movement to the needle, which records the duration and the phases.

sists of a metal capsule, with a gutta-percha membrane stretched over the top; a lever is attached to the membrane by means of a jointed crank. If the first lever is pulled by the hand and lowered, the air in the first tambour is compressed and passes into the second, the corresponding lever is raised, and reproduces in all its phases the traction exercised on the string. On

* Usually called "Marey's Tambours," in England.—TRANSLATOR.

the hand being released, the opposing force brings the first lever back into its original position, the air returns from the second into the first tambour, and the lever of the second falls in consequence. Thus the movements produced by raising or lowering the hand are transmitted after an inappreciable delay (*i.e.* that of sound) to a lever which can record them on a revolving cylinder which has been covered with paper. Now, the record can be written in two ways: either according to the Morse Code, by making or breaking the contact between the pen and the surface of the cylinder, or else in the form of a continuous curve, the variations of which express the different phases of the movement.*

Chronographic Record of the Foot in Walking, as it touches and leaves the Ground.—A cylinder which turns at a uniform rate is covered with a sheet of paper, while the points of two tracing needles, which are placed side by side, touch the surface of the cylinder, one of them at the moment the right foot, and the other at the moment the left foot reaches the ground. The object of the arrangement is that each needle shall come in contact with the surface of the paper as the corresponding foot touches the ground. The transmission is effected by means of pneumatic tubes.

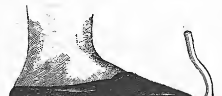

FIG. 3.—Shoe for indicating when a man s foot comes in contact with the ground; a transmitting tube effects a communication between the air chamber and the chronographic tambour.

A particular kind of shoe (Fig. 3) is fitted to the foot of the pedestrian, and the sole is composed of a thick

* For the different applications of this sort of written record see "The Graphic Method," p. 426.

sheet of indiarubber, provided with a hollow chamber. This latter cavity communicates through a long flexible tube with the recording tambour. Each time the foot touches the ground the air within the cavity of the sole is compressed, and passing along the connecting tube raises the corresponding recording needle. The pedestrian furnished with a pair of these shoes (Fig. 4), carries in his right hand the recording apparatus with its registering needles. When he wishes the tracing to commence he squeezes an indiarubber ball which he holds in his left hand; if, a moment later, he releases the pressure, the needles cease tracing. Records are thus obtained which vary according to the pace, the weight carried, and the incline.

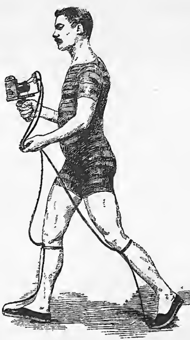

Fig. 4.—Pedestrian furnished with special shoes and carrying a chronographic apparatus.

Changes in the sequence and duration of the footfalls are shown by the four figures in the diagram (Fig. 5). In this the contact of the right foot is represented by a white, and that of the left by a diagonally shaded line. The first of the series represents walking on level ground. The steps of the two feet are alternate and regular. The second tracing is obtained by walking upstairs; in this, one foot does not leave the ground until the other one has been down some time. This represents

one of the phases of reduplicated footsteps. The third is that of a runner. The periods of contact are short, and separated from one another by intervals

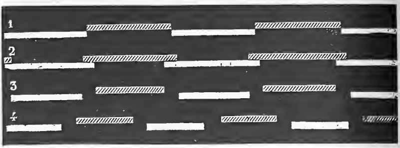

FIG. 5.—Chronographic record of the periods of contact of the feet of a man executing various paces.

during which neither foot is in contact with the ground —a period of suspension. The fourth tracing is one of a man running at a greater speed, the periods of contact are shorter and the intervals longer.

Record of the Rise and Fall of the Four Feet of a Horse in its Various Paces.—For some time past specialists gifted with immense powers of observation have set themselves the task of determining the real character of the various paces of a horse from observations on the sequence of the *beat* of the feet. The use of the word *beat* implies an attempt to recognize from the sound of the footfalls the sequence of the moment of contact, the question of duration being neglected. Moreover, the sense of hearing is above all others capable of appreciating intervals of time. The effect has been tried

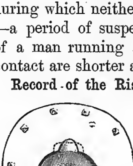

FIG. 6.—Special apparatus for recording the contacts of a horse's feet with the ground; a transmitting tube effects a communication between the air chamber and the chronographic tambour.

of providing horses' legs with bells which emit different notes as each foot touches the ground. All of these experiments have left doubts as to the exact rhythm of the various paces, doubts which have only been cleared up by the application of chronography. The following method has been employed in this research: indiarubber balls stuffed with hair are fixed under the hoofs of the horse, and kept

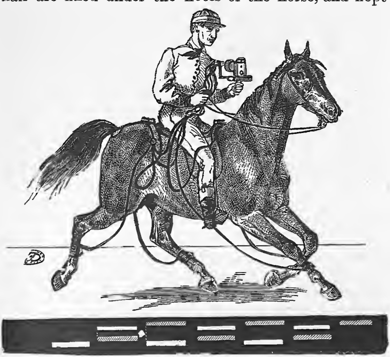

FIG. 7.—Horse at a *full trot*. The point indicated on the chart corresponds to the position of the horse represented in the figure.

in position by calkins which screw into the metal of the shoe. Each of these balls is in connection with a long indiarubber tube which is fastened to the horse's legs by flannel binders. These tubes communicate with the recording apparatus. The latter is provided with a tracing needle, and held in the hand of the rider (Fig. 7). The pressure of the feet upon the

ground compresses the balls with which they are provided, and forces the contained air into the recording tambours. The method tallies in all respects with that employed in the case of man. However, on account of the multiplication of writing needles, which the greater number of footfalls necessitates, the four needles are grouped in two series, one to record the movements of the fore feet, and the other placed beneath it to record the steps of the hind feet. In both series, the white lines indicate the movements of the right feet, while diagonally shaded ones represent those of the left.

Fig. 8 shows results obtained in this way of the three ordinary paces, namely, ambling, walking, and trotting.* It will be noticed that each record is represented as a series of four tracings, such as would be obtained by arranging in parallel series the tracings of two men walking. In fact, a quadruped may be compared to two bipeds—to two men, for instance—walking one behind the other, one to represent the fore, and the other the hind limbs. Such a pair would take the same number of steps; but the phases of rest and motion would assume different relations in the two cases. It is this which constitutes the difference between the various kinds of paces. For instance, when the corresponding hind and fore feet move simultaneously, the horse is ambling (Fig. 8, first record). If the right fore foot is in the mid phase of rest when the left hind foot reaches the ground, the horse is walking (second record). Lastly, if the anterior and posterior legs move in opposite pairs, *i.e.* if the anterior right reaches the ground at the

* It is more than twenty-one years ago that these experiments were made, and we remember with gratitude the patient assistance with which Messrs. Pellier and Gabriel Paillard helped us to carry them into effect.

same time as the posterior left leg, the horse is trotting (third record). It is thus seen with what simplicity the ordinary paces of a horse may be recorded both as regard sequence and duration.* Paces that involve a springing movement, *i.e.* the various forms of galloping, can be analyzed with equal facility in spite of their greater complexity.

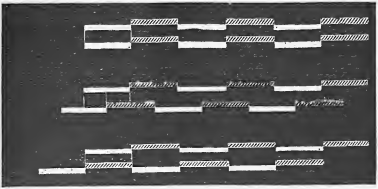

FIG. 8.—Three records of the paces of a horse: amble, walk, and trot.

Fig. 9 is the record of the ordinary *triple-beat* gallop, *i.e.* that in which the combined fall of the hoofs produces three sounds appreciable to the ear. The diagram shows how the three sounds are produced.

The simple interpretation of this written record is that, in A, the first sound is made by the left hind foot. The second by the simultaneous fall of the left fore, and of the right hind foot. The record demonstrates still another fact, for, in B, it can be seen by what feet the body is at any moment supported. It is clear that at first the weight falls only on one leg, then on three, and then successively on two, three,

* In this record we have represented the trot as a walking pace, this is an exceptional case. The ordinary trot is a form of running, and its graphic record shows a moment of "suspension," as in the case of a man running.

and one. In the final stage, the horse is momentarily poised in the air before it again comes down on the left hind foot.

The Record of the Fingering of a Pianist.—The facility with which chronography can be applied to the most complicated movements of irregular sequence and duration has encouraged an attempt to record movements so complex as to defy the observation of the most practised, namely, the movements of the fingers of a pianist on the keyboard of his instrument.

Under each note on the keyboard of a harmonium is placed a tiny pair of bellows, and each of the latter is in communication by means of a special tube with

FIG. 9.—*Triple-beat* gallop. A indicates the exact position of the three *beats*. B indicates the number of feet by which the horse is supported at any particular moment during a *triple-beat* gallop.

a corresponding pair, which in turn are connected with a tracing needle. The series of needles are placed in a row, and are arranged in the order in which the different notes succeed one another in ordinary music, namely, in an ascending scale of musical pitch. All these needles trace their record on a strip of smoked paper which is moved by clockwork. Finally, a comb with five teeth inscribes the stave on which the various notes are written and recognized by their respective positions in relation to it. The duration of the sound is expressed by the length of the stroke. Semitones are distinguished by two tiny parallel strokes, instead of a single broad one.*

* This method of notation has been made use of by M. V. Tatin in a very able manner.

At one of the scientific soirées at the Sorbonne, during a conference on animal movement,* one of our associates, a celebrated organist, kindly played some pieces of music which recorded themselves before the eyes of the audience, and of which we here give two examples (Fi 10, A and B). Every one who is

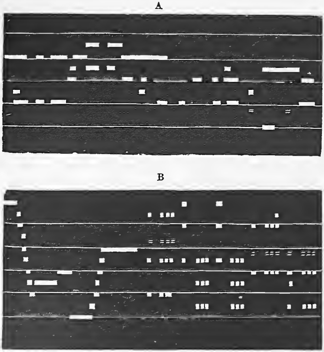

FIG. 10.—Record of two airs played on the keyboard of a harmonium.

accustomed to read ordinary music will easily decipher these examples; they only differ from the ordinary score by the way in which the duration of the note is expressed. Instead of the conventional method of expressing the duration of different sounds by minims, crotchets, and quavers, and the duration of silence by rests and crotchet-rests, the graphic method conveys

* See *La Nature*, 5th October, 1878.

the same impression by the length of the stroke, that is to say, by a natural graphic expression.*

The Uses of Photography in recording Time.—If the recording needle cannot be applied to the study of any particular phenomenon, recourse must be had to photography. It is by this means that a system of optical telegraphy has been perfected, by which flashes of light can be transmitted from one point to another, and received as a series of dots and dashes, such as constitute the Morse Code.

The luminous point at the transmitting station is alternately, and at various intervals, exhibited and obscured by the movement of a screen. This constitutes the transmitting apparatus. The rays of light emanating from this source are rendered parallel by the interposition of a lens, and traverse the intervening space to impinge upon a similar lens at the receiving station.

At the focal point of this second lens the image of the luminous source is visible in the form of a brilliant spot. If the sensitive surface, upon which this image falls, is allowed to travel at a uniform rate, short flashes of light will produce spots, and sustained flashes will give lines. An arrangement of this kind has many scientific applications, but it is not in this manner that photography has been most usefully employed in time-measurements. It has chiefly been utilized for two purposes. Firstly, to

* During late years many inventors have constructed similar machines, and we believe that even this is not the first which automatically inscribed an air executed on the piano. Among instruments of recent design there is a very remarkable one, which we owe to Messrs. Cros and Carpentier, and which is known as the "Melograph." This instrument is not intended to register the air as played by the artist, but it perforates a strip of paper in such a way that when it is repassed through the machine the piece of music which has been executed by the operator is reproduced by it with perfect fidelity.

measure the exposure of a photographic shutter; and secondly, to measure the intervals of time which separate consecutive exposures. Both of these methods must be described, since it is necessary to be familiar with them, so as to understand the analysis of movement by means of photography.

Measurement of the Duration of Exposure produced by a Photographic Shutter.—Shutters are generally called *instantaneous*, when they show in the photograph a representation of a moving object as clearly as would have been the case had the object been at rest. This definition is not, however, strictly true, since shutters, capable of giving a clear picture of passengers in the street, may be incapable of doing so in the case of the hoofs of a trotting horse. A still shorter time is required to catch the various positions of the wing of a flying bird, and still more so in the case of insects. It must be possible then to measure the exposure of a shutter, and express the time in fractions of a second.

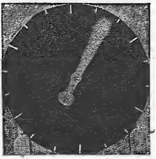

Fig. 11.—Needle spinning round the chronometric dial, and measuring the duration of exposure.

We shall see how photography allows this measurement to be made. Let a bright needle rotate on a dial (Fig. 11) covered with black velvet, and graduated by white lines. The movement of the needle must be absolutely uniform. For this purpose clockwork machinery with a Foucault's regulator is employed. This mechanism is hidden behind the dial, and the needle makes one complete revolution in a second and a half, say 90‴. The circumference of the dial is divided into eighteen equal parts, and consequently the contained angle of each space corresponds to 5‴.

While the needle is constantly rotating, we must focus on the dial a camera provided with the shutter, the exposure of which we wish to ascertain. The opening of the shutter is effected by pressure on an indiarubber ball. If the period of exposure is not extremely short, the image of the needle will not be clearly defined, but will occupy a more or less extensive segment of the dial. In such cases it would be impossible to determine with any exactitude the number of degrees occupied by the image. This is due to the construction of the shutters, which give incomplete illumination at the beginning and end of the exposure.*

From the blurred nature of the image, which obscures the exact contour of the needle, one can only approximately estimate that the distance travelled during a single exposure is about three or four degrees, which corresponds to about $\frac{1}{25}$ of a second.

It is almost impossible for a shutter, which gives a single exposure, to produce one of very short duration. For this object, the spring which moves the shutter must be very powerful, and the weight carried extremely light. With shutters of this kind it is possible to reduce the exposure to $\frac{1}{200}$ of a second.

The shutters referred to in this work are of special construction. They consist of fenestrated diaphragms which, by means of continuous rotation, are able to acquire immense velocity. Their fenestrations, moving within the lens with extreme rapidity, produce a succession of illuminations of very short duration.

It is this which gives such good definition to the images, which are shown in Fig. 12. Further, the

* To obtain a true idea of the outline of the needle, it should be compared with the image of Fig. 12. In this case the exposure has been short enough to prevent any alteration in its shape through the movement.

images succeed one another at absolutely regular intervals, because both the movement of the needle on the dial and that of the circular diaphragms are equally uniform.

Measurement of the Intervals of Time which separate Successive Exposures.—By reason of the clear definition of the images, they can be accurately measured, not by the time of exposure, which is too short to be appreciated, but by the intervals of time between successive exposures. Now, this is the important point in the measurements which we shall have to make of the duration of certain phenomena.

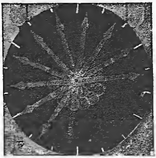

FIG. 12.—Successive positions of the needle on the chronometric dial, measuring the intervals of time separating the successive exposures.

Provided that one can arrange a reliable clockwork mechanism so as to move the needle round the dial at a uniform rate, it does not matter what rate of movement is imparted to the circular diaphragms, the interval between two exposures can always be measured by the angle contained between two consecutive images of the needle. If, during the time, an object, visible in the field of the lens, happens to move, there will be found, on the sensitized plate, several of its images in various positions and at various distances from one another. For the purpose of measuring the intervals of time between such successive positions of the object, the changes in position of the needle on the chronographic dial will serve as an index.

The further applications of this kind of time measurement will be seen when we come to discuss Chronophotography.

CHAPTER II

SPACE

Its Measurement and Representation by Photography

Summary.—Tendency to replace outline drawings, plans, and diagrams in relief by photography—Photography traces the various positions in space occupied by a moving body—Photographic trajectory of the movements of a point in space; its stereoscopic trajectory —Movements of a straight line in space—Solid figures formed thereby: cylinders, hyperboloids, cones, etc.—Movements of a curve in space; photography of the figures which it forms: spheres, ellipsoids, etc.—Stereoscopic pictures of figures of three dimensions—Figures formed by the movement of solid bodies; effects of light and shade.

Tendency to replace Outline Drawings, Plans, and Diagrams in Relief by Photography.—The positions of bodies in space, their forms and dimensions, find their natural expression in geometrical drawings. Such drawings, executed to a known scale, supply all the information that is required.

During the last few years, however, there has been a tendency to substitute photography for outline drawings, and doubtless in the future it will completely replace them. Indeed, it supplies with remarkable ease pictures of undoubted accuracy. The dimensions can be enlarged or reduced as occasion may require, and if thought desirable, a scale for the purpose of measurement may be introduced into the picture, and

the exact dimensions thus indicated. To introduce such a scale into the picture, a rule with very distinct divisions must be placed by the side of the object which is being photographed. When an artist wishes to represent in relief an object of three dimensions, he must obey the laws of perspective, and take into consideration the manner in which the light falls on the object, at the moment of drawing. But the fitful changes of light, during the various times of day, offer innumerable difficulties.

Photography, however, gives an instantaneous picture of the most diverse objects, and that, too, with the prevailing conditions of light, and all in correct perspective. The appearance of natural objects, as seen by looking with one eye only, is thus reproduced by photography. If it is required to get the effect of relief, such as is obtained by looking with both eyes, recourse must be had to stereoscopic pictures.

Photography traces the Various Positions in Space occupied by a Moving Body.—When an object changes its position, it is often necessary to notify the positions in space which it successively occupies. In the first place, we must be quite sure that our eyes have been able to follow the various phases of movement, and that our memory has been able to retain the details—conditions rarely fulfilled—before we have recourse to drawing, as a means of representing the trajectory described. The diagram traced will be more or less complicated according as we express the movement by a point, a line, a plane superficies, or a solid—in short, according as we represent a movement executed in one or more directions.

When it is only a question of the movement of a point, in certain cases the difficulty may be met by making the moving point itself trace the path which

it takes.* It must be possible, however, to fasten this point directly or indirectly to the needle which is to trace the trajectory, and, further, the propelling force must be sufficient to work the mechanism of the recording instrument, and that, too, without modification of the movement. But if the point is inaccessible, if the propelling force is too feeble, or if it follows a very complicated course, we must introduce new conditions, and employ photography in the special manner we are about to describe.

Principles of Photography with a Dark Background.—When a camera faces a dark background, no impression is made on the sensitized plate, because no light reaches it; but if a very luminous object is placed between the background and the lens, light will be reflected and an image imprinted on the plate. If, while the object-glass is uncovered, the white object changes its position, there will be reproduced on the plate a track which exactly corresponds to the movements of the object. This is the trajectory of the object, or, to put it more precisely, the projection of its trajectory on the surface of the sensitized plate. The image will be more or less reduced in size according to the distance of the object, and according to the focal length of the objective.

Photographic Trajectory of the Movements of a Point in Space.—To demonstrate the advantages offered by photography as a means of recording the trajectory of a moving object, we will choose as an example a case in which direct observation will afford us no information, and in which a mechanical method of recording will be impracticable. Suppose, for example, that we wish to ascertain the various positions in space

* The different proceedings for mechanically recording the movements of a point in one or more directions in space have been given in "The Graphic Method."

occupied by a particular part of a bird's wing during the act of flight, and that this particular part is the tip of one of the quills, called "remiges." Now, such a quill, by reason of its flexibility, would be incapable of giving the necessary motive power to an apparatus for recording the trajectory of flight; and, further, this point is inaccessible because birds only fly freely at a certain distance from the observer. A black crow may be used in the experiment, and a small piece of white paper may be fixed to the extremity of one of its

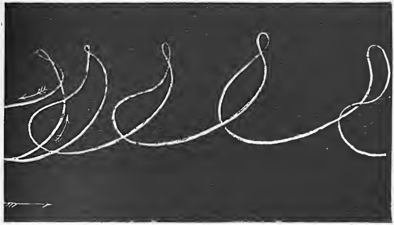

FIG. 13.—Trajectory of the tip of a crow's wing. A brilliant spangle attached to the second of the *remiges* follows the path indicated by the small arrows. In the lower part of the figure a straight and horizontal arrow shows the direction of flight.

longest "remiges." The bird is then allowed to fly in front of a dark background, towards which a photographic camera is directed. Since the entire field of the object-glass is dark, that is to say, the bird and its background, the sensitized plate can receive no light except that which is reflected by the small piece of white paper, which is illuminated by the sun. The image of this white spot will leave a record of its track on the sensitized plate. In this way Fig. 13 was obtained, the arrows indicating the direction of flight.

Stereoscopic Trajectories.—The trajectory of the

movement of the point of a wing cannot be expressed comprehensively in the form of a plane diagram, since the movement of the wing at the shoulder-joint takes place in three directions. The photographic diagram only gives one projection of this trajectory. It is thus incapable of expressing the real course of flight taken. If a movement takes place in three directions, recourse must be had to a more complicated arrangement, and a stereoscopic trajectory obtained. Let us take the case of a man walking away from us, and concentrate our attention on a particular point of his body. This point is elevated and depressed as the man's foot rises and falls. Further, it is affected by the side-to-side swing, and according to the direction in which he walks. The pedestrian must be completely dressed in black, and a bright metal button fastened to a part of his body. The man is then made to walk in front of a dark background, and a stereoscopic photographic camera with two lenses is focussed on the spot. Both of these object-glasses, acting precisely as the single one in the preceding experiment, produce two images of the luminous point.

Fig. 14 was obtained in this manner; it shows two images of the same trajectory taken from two different points of view. Examined with the stereoscope, these images stand out in bold relief.*

* Since a considerable number of people are able to see figures of this sort standing out in relief without having recourse to a stereoscope, we have published the above figure, and certain others will be found further on. To obtain the full effect of relief without a stereoscope, we must concentrate our vision on a distant point, and then interpose the object between our eyes and the distant point. The page of the book will then be seen double, and consequently the trajectory will appear as four separate images. If the book is then very gently moved, and the direction of the eyes slightly altered, the two internal images finally become exactly superimposed. The eye is then accommodated for distinct vision of the central image, which stands out in relief between the two outlying images.

With a little practice one can easily dispense with the stereoscope for examining figures of this sort.

Movements of a Straight Line in Space. Photography of the Solid Figures formed thereby: Cylinders, Hyperboloids, Cones, etc.—A straight line, which is moved in various ways on a plane surface, covers the latter with a variety of configurations, or else, if attention is paid only to the various positions which it occupies at certain moments, these positions can be expressed

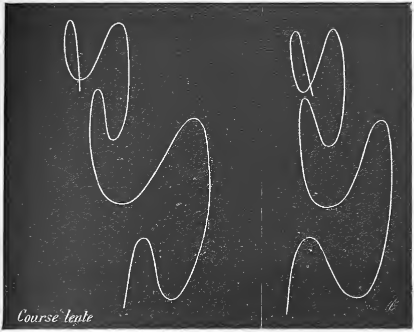

FIG. 14.—Stereoscopic trajectory of a brilliant point placed at the level of the lumbar vertebræ of a man walking away from the photographic camera.

as geometrical figures, which can be transferred to paper; but if this straight line moves in the three directions of space it describes surfaces, the projections of which can only be represented by perspective drawing. In such cases recourse must be had to diagrams in relief, which have the advantage of giving beginners a clearer notion of solid forms. By means of threads stretched between metal armatures, one can

show how the successive positions of a straight line can produce cylinders, cones, conoids, and hyperboloids by revolution. There is a particularly rich collection of such diagrams at the Academy of Arts and Crafts—very useful as a means of popularizing the study of solid geometry.

Now, if the geometry of to-day has become purely a speculative science, there is no doubt that, like all other sciences, it had an experimental origin. It is not likely that the conception of a straight line was evolved from man's brain as a purely abstract expression, but rather that it entered therein, on seeing a stretched thread, for instance, or some other rectilinear object.

In the same way the conception of a plane or a circle found its origin from noticing a flat surface or an object of circular form.

There are, so to speak, traces of these concrete origins of geometrical figures in the definitions given to solid figures or to those of three dimensions.

Such objects are said to be "engendered" by straight lines or curves, which undergo various displacements. Thus a regular cylindrical surface is engendered by a straight line which moves parallel to another straight line, and yet remains at the same distance from it. The straight line which moves is the "generator" of the cylinder; that which remains fixed is its axis.

Under such circumstances, let us suppose that the straight line, as it moves in space, leaves a record of its track at every point which it successively passes. Now, this purely imaginary supposition may become an accomplished fact, thanks to photography. Indeed, supposing we take a series of instantaneous views of an illuminated thread as it moves in front of a dark screen, figures are produced which exactly resemble the stereoscopic forms obtained by stretching a series

of threads between metal armatures. This is the method :—

A vertical metal rod furnished with two transverse arms, which are exactly opposite to one another, is allowed to rotate in front of a dark screen. This metal frame must be blackened with the smoke of a candle, and thus rendered as nearly invisible as possible. The two cross-bars must be of equal length, and their free extremities connected by a white thread, which is stretched vertically between them. This thread, by means of the rotatory motion which is imparted to the two cross-bars, moves in a circular manner round the axis, and describes in space the circular outline of a cylinder.

A photographic camera directed towards this thread, and kept permanently open, would receive an image, which would be the projection of a cylinder on a plane surface. But this continuous trajectory would not show its method of production with sufficient clearness. In order that one may see that such a picture results entirely from the movement of the thread, which at every moment adds a new component-element to the surface of the cylinder, separate images, at successive intervals of time, must be obtained. That is to say, the light must be admitted in an intermittent manner. Fig. 15 was thus obtained.*

If the thread, instead of lying parallel to the axis round which it rotates, is directed obliquely towards it, the figure described will be a hyperboloid by revolution (Fig. 16). And, finally, if the thread is

* In this diagram the central axis appears white, because, although the amount of light reflected from such a blackened surface is extremely feeble, nevertheless, this light is always reflected on to the plate every time the objective is uncovered.

Now, since the axis remains permanently in one place, each separate impression, however feeble, is superimposed on the same part of the sensitized plate, and ends by being clearly defined.

placed still more obliquely—in fact, if it touches the axis at one point—the figure described will be a cone.

Photography, with a dark background, is especially adapted for demonstrating the construction of cones and hyperboloids; and, further, it clearly shows the relations which these two kinds of figures bear to one another.

An indefinite number of images can be taken on

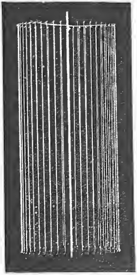

FIG. 15.—Cylinder engendered by the displacement of a white thread moving round a central axis.

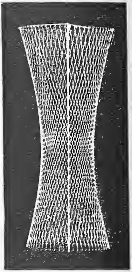

FIG. 16.—Hyperboloid by revolution: a single web engendered by the revolution of a thread set obliquely to the axis.

the same plate. No sooner has one image been taken than another can be superimposed; the second impression is just as good as the first. This method was employed in the production of Fig. 17. After having taken a photograph of a hyperboloid by revolution, the dark slide was closed, and the thread arranged so as to describe a cone; the slide was then opened again, and the image of the cone obtained. The two pictures

thus superimposed show the hyperboloid on the outside and its asymptotic cone inside.

Conoids.—If the white thread, instead of revolving round the axis, as in the experiment which we have just been reading, has imparted to it at one extremity a rotatory motion, while the other extremity moves in a straight line, one obtains, according to the relationship of the two movements, different sorts of conoids, of which Fig. 18 is one example.

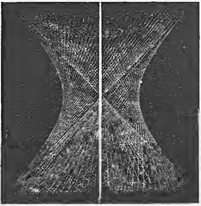

FIG. 17.—Hyperboloid by revolution with its asymptotic cone.

Movements of a Curve in Space. Photography of the Figures which it forms: Spheres, Ellipsoids, etc.—Among

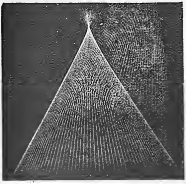

FIG. 18.—Conoid engendered by the movement of a white thread.

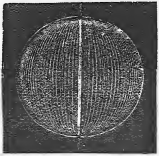

FIG. 19.—Sphere engendered by the rotation of a semi-annular white thread.

the forms arising from the movements of a curve, the most easy to produce is a sphere; it is obtained when

a semicircular wire of white metal rotates round a vertical axis, which is also its diameter. Fig. 19 is the projection of such a sphere on a plane surface. (The imperfections of the figure are due to the fact that it is impossible to impart perfect regularity of curvature to the wire which constitutes the semicircle.) It is unnecessary to multiply examples of figures

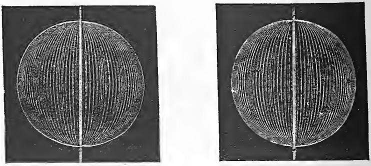

FIG. 20.—Sphere engendered by the rotation of a semi-annular thread. (Stereoscopic images.)

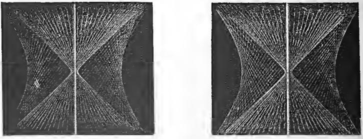

FIG. 21.—Hyperboloid and its asymptotic cone. (Stereoscopic images.)

generated by the movement of curves, such as ellipsoids, paraboloids by revolution, etc.

In order that these figures of three dimensions may be rendered more intelligible, we have reproduced them in the form of stereoscopic pictures by the following proceeding.

Stereoscopic Pictures of Figures of Three Dimensions.—We must provide ourselves with a stereoscopic camera

with two object-glasses of equal focal lengths. The mountings of these objectives must be cleft by a deep slot, perpendicular to their axes; and within this slot there must rotate a diaphragm perforated by two openings, which are diametrically opposite to one another. This diaphragm rotates at a uniform rate, and simultaneously uncovers the two objectives; during each complete revolution of the diaphragm the objectives are twice uncovered. A mechanical motor turns the circular diaphragm, and, by means of a pulley

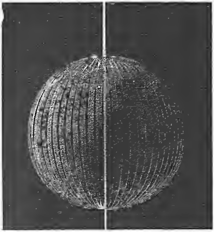

FIG. 22.—Sphere engendered by the rotation of a semi-annular band, white on the outer surface and black on the inner side.

and continuous band, the same motor serves to turn the axis and the white threads. The latter, by their movements, describe the desired figures.

Figures formed by the Movement of Solid Bodies; Effects of Light and Shade.—Instead of the fine thread, which has just served our purpose for describing the surface of a sphere in space, let us take a solid body; the appearance of the figure described will be quite different. A band of Bristol board is arched lengthwise, its convex surface blackened, and its concave

surface left white; when such a band rotates, a figure such as Fig. 22 will be produced. Except for certain breaches of continuity, due to the intermittent character of the illumination, the surface thus produced will resemble that of a solid sphere, which is illuminated from the left and from above, while the opposite side is only feebly lighted by reflection. This appearance is easily explained. The strip of paper, as it travels over successive meridians of this imaginary circle, is placed under exactly the same conditions of illumination as would be the case if the meridians were those of a real sphere in the same position.

Paradoxical Effect produced by Certain Conditions of Illumination.—Instead of the strip of paper used in the preceding experiment, and from which light was only reflected from the convex surface, let us take a strip of similar board, only white on both surfaces. We shall thus obtain a peculiar effect (Fig. 23) which can only be understood when viewed under stereoscopic conditions.

The inner and outer surfaces of this sphere can be seen at one and the same time. This is because the arc of Bristol board is white within as well as without, and consequently reflects the light, sometimes from one surface, sometimes from the other, according to the position of rotation. When the convex arc faces the light, *i.e.* is directed upwards and towards the left, the corresponding portion of the engendered sphere is clearly visible. When the arc is in an exactly opposite phase of rotation, it receives the light on its concave aspect; that is to say, the interior of the sphere below and on the left is the part illuminated.

At first sight this figure appears to be transparent, but on the one hand we know that it has been formed by an opaque substance, and on the other that all known transparent media reflect light in a totally different manner.

In reality we are dealing with a hypothetical figure, which finds no counterpart in Nature. Such hypothetical figures are still more strange, when, instead

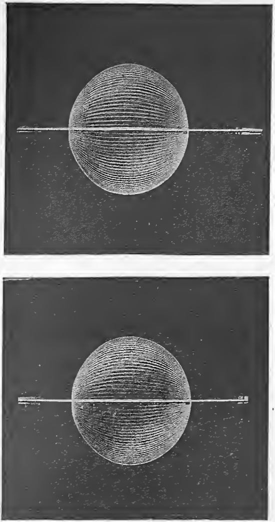

Fig. 23.—Sphere engendered by a semi-annular band, white on both surfaces. (Stereoscopic images.)

of dull substances being employed in their construction, a polished material is made use of which only reflects the sun's rays from certain points of its surface.

Fig. 24 was obtained by allowing a semicircular arc of polished brass to rotate round a vertical axis. There is for each position of rotation only one particular spot on the polished metal arc from which the incidental rays of the sun can be reflected into the body of the camera. Now, as this bright spot changes its position, it is sometimes on the convex side and sometimes on the concave side of the metal arc. It is the displacement of this luminous spot which traces the complete rings on the opposite portions of the sphere.

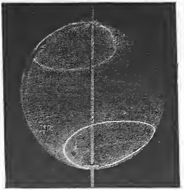

FIG. 24.—Paradoxical appearance of a sphere engendered by the rotation of a brilliant metallic thread.

In order more clearly to understand the causation of this peculiar appearance, we must have recourse to stereoscopic figures, with an intermittent series of images. Such figures show that in each position certain portions of the surface of the semicircular arc are dark, that is to say, do not transmit light in the direction of the photographic apparatus; on the contrary, other points are brilliantly illuminated, because in this position they are "set," so to speak, so as to reflect the sun's rays. These curious effects can never be caused by a real body. The form and position of the illuminated spots on the sphere can be varied at will by changing the direction of incidence of the luminous rays.

The mathematical study of these diverse effects would be, perhaps, rather complicated; in any case, it would afford a very limited amount of interest. It was necessary, however, to mention them, because in the course of our studies, we shall meet with analogous forms, produced by the movement of certain bodies.

CHAPTER III

MOVEMENT

Its Measurement, Graphic Representation, and Analysis by means of Chronophotography

Summary.—The understanding of a movement implies a double knowledge, namely, that of space as well as that of time—Graphic representation of a movement—Chart of a train travelling along a line—The curve of a prolonged movement should be recorded in sections—How a moving body can record its own movement—Proportional enlargement and reduction of the recorded movement—Odography—Photographic record of movement—Photography of the movement of Lippmann's electrometer—Determination by means of chronophotography of the movements executed by a falling body—Construction of the curves of movement from chronophotographic images—Time-curve of the distance traversed—Curve of velocity—Curve of acceleration.

The Understanding of a Movement implies a Double Knowledge, namely, that of Space as well as that of Time.—We saw in Chapter II. that photography could reproduce the trajectory of a body moving in space; but the idea there conveyed of the successive changes in position was not sufficient to define the movement. The power to do so presupposes a knowledge of the relationship existing at any moment between the distance traversed and the time occupied. Now, the object of Chapter I. was to demonstrate that photography would permit the exact measurement of time intervals. It follows that, if the two notions of time and space can be combined in photographic

images, we have instituted a chronophotographic method, which explains all the factors in a movement which we want to understand. It also affords a very simple experimental solution of certain very complicated mechanical problems. The whole question of *mechanics* is based on a knowledge of the movement which is imparted to a mass; for from the movement the force which produces it can be measured.

To determine with accuracy the character of a movement, whether it be uniform or irregular, to determine its velocity and degree of acceleration extremely delicate experiments are usually necessary.

When the movement is once thoroughly understood, its character must be expressed in a precise manner. Since the time of Descartes, geometricians have known how to express the characters of movements in the form of curves with different variations. But such curves, although they can express certain phenomena, require, like other geometrical figures, a more or less laborious construction. It was a great step in advance when Poncelet and Morin showed that a moving body could itself be made to trace its path in the form of a curve. The first application of this graphic method was made use of in the case of a falling body; it was soon, however, extended to other branches of Science. Meteorology, Physics, and Physiology all participated in the discovery with advantage to themselves.

In spite of the enormous development of this method, it has limitations, which we can only extend by the employment of chronophotography. Thus, when the moving body is inaccessible, when it cannot be fastened by mechanical means to the recording apparatus, this new method for determining its movement must be employed; a method which demands no material link

between the visible point and the sensitized plate on which from moment to moment its movement is recorded. To fully appreciate the advantages of chronophotography, it will doubtless be best to compare it with other methods already employed in the solution of the same problems. Let us take the most simple case, that of recording the displacement in a straight line of a moving body, and let us approach the question in accordance with the two methods.

Graphic Representation of Movement.—When a point travels along a straight line, the successive positions can be indicated by means of two straight lines at right angles to one another. These two straight lines, the one horizontal and the other vertical, indicate respectively the time taken and the distance traversed. If the moving body is propelled at a uniform rate of one hectometre to the minute, this movement can be expressed by the oblique line which joins the points where the divisions of time and space intersect (Fig. 25). This is the curve of movement. In the case of a uniform movement, this line is always straight: but it will be more or less obliquely inclined according to the speed at which the body travels. Thus, for double speed, that is to say, two hectometres in the minute, the line will pass through the point at which the second division of space and the first division of time intersect. It will thus form the diagonal of a series of rectangles, the sides of which will be formed of two space-divisions and one time-division. This system of representation expresses

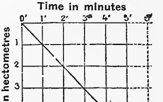

FIG. 25.—Graphic representation of a uniform movement.

all degrees of speed and all kinds of movement. A horizontal line signifies a period of rest, and the length of the line, or, in other words, the number of divisions which it occupies, is a measure of the duration of this period of rest.

Irregular movement is expressed by a curve, the inclination of which, *i.e.* the tangent, indicates from moment to moment the rate of progression. Further, each point of the curve indicates according to its relation to the horizontal and vertical scales the time occupied and the distance travelled since the commencement of the movement.

Chart of a Train travelling along a Line.—A geometrical expression for all sorts of movement has become now almost universal, since the engineer Ibry made use of it to chronicle the progress of trains along a railway. Nowadays every one is familiar with these charts, in which are to be seen lines intersecting one another in all directions. Variations both as regards inclination and direction express the speed and the route taken by all trains running on the track. Fig. 26 is an example of such a chart placed by the directorate at the service of its employés. To the left of this chart, along the axis of the uprights, are printed in series the names of the various stations. These stopping-places are separated on the chart by intervals proportional to the number of kilometres which actually intervene as they occur on the line. In the horizontal direction, *i.e.* along the axis of the abscissæ, time is registered by periods of an hour; these are again subdivided into periods of ten minutes.

To indicate that a train should arrive at a given hour at a particular point on the line, its position is marked on the chart opposite the station at which it is expected, and vertically above the division which corresponds to the time at which it is due. As the

train proceeds on its way particulars are notified, both as regards the direction in which it is going and the time occupied. But if the train stops, its place on the chart only changes as far as the time-axis is concerned, and consequently the stoppages are ex-

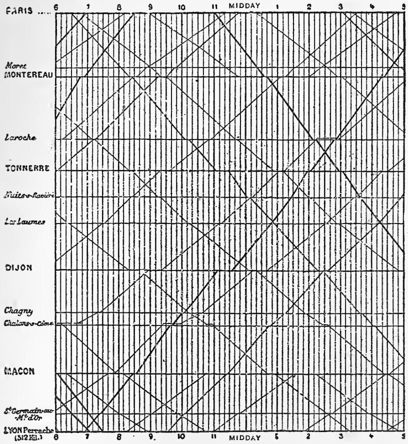

FIG. 26.—Chart to express the movements of trains along a railway. (Ibry's method.)

pressed by horizontal lines more or less elongated. The inclination of the line expresses the speed of the train. The faster the train moves the more nearly vertical does the line become. Express, fast, through, and stopping trains can thus be distinguished at a

glance. The direction of the curve indicates the destination of the train. Lines descending towards the right represent trains going away from Paris, while those which ascend towards the right correspond to trains going towards the capital. The intersections of lines on the chart signify the places and the hours at which trains cross one another *en route*. This admirable mode of representation is the only one which should be employed to express in a graphic form the trajectory of a moving point. In such tables the rate of progress of the trains is supposed to be uniform, and is represented by straight lines instead of irregular curves. The latter are employed to express a change of speed as it occurs from moment to moment. This is the only way in which such a mode of graphic representation deviates from what actually occurs. It is improbable, however, that any serious difficulty would arise from this cause.

The Curve of a Prolonged Movement should be recorded in Sections.—Charts used to express the movements on a railway are crowded with detail, because they record the progress of every train which moves in one or other direction along a more or less extensive section of the line. The surface of the paper is thus completely utilized. But this would not be the case if we had to record the progress of one train only during a long run extending over many hours. On referring back to Fig. 25 it will be noticed that the diagonal of the square expresses a journey of six hectometres completed in six minutes. Now, for a journey twice as long, and taking twice the time, the diagonal would be double the length, and the square containing it four times as large. According to this geometrical progression, we should have to use a sheet of paper a metre square if we wanted to record the progress of a moving body for twenty kilometres.

And this immense surface would only be broken by a single fine line dividing it diagonally into two parts. This inconvenience would in itself serve to condemn the method from a practical point of view. It can be avoided, however, by dividing the tracing into sections, each of which expresses the movement during a given time. Thus Fig. 27 shows concentrated on a narrow strip of paper the various phases of a movement which otherwise would have required a surface six times as large.

On this strip of paper the scale representing distance is continuous, but that representing time is broken. After each period of five minutes the curve returns to the first time-division, but remains on the distance-division at which it has actually arrived. From this point a new section of the curve recommences. The sections A, B, C, etc., thus express the progress of the moving body over a distance of 25 hectometres, and during a period of 30 minutes, and the curve is quite as intelligible as would be a continuous one requiring a large surface of paper.*

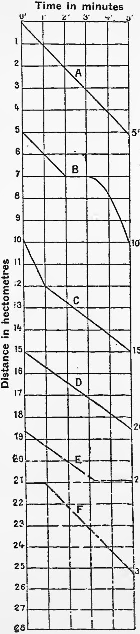

FIG. 27.—Successive sections of the curve of a movement.

* The section A shows that, during the first five minutes, the moving body

How a Moving Body can record its Own Movement.—Poncelet and Morin solved this problem by constructing the well-known machine which registers the movement of a falling body. In this machine, the falling body is provided with a needle, which leaves its record on paper, and moves in a vertical direction at the same rate as the falling body. Further, the paper rolled round a revolving cylinder advances in a horizontal direction at a uniform rate. When the paper is taken off the cylinder, the needle is found to have traced a curve which is parabolic in form. This is the geometrical manner of expressing a movement of uniform acceleration. This machine is a type of the recording apparatuses of which there are nowadays a considerable number. It must be mentioned at the same time that, by reason of its construction, it can only record the curves of movement to actual scale; it could not, therefore, be used to represent movements too small or too extensive to be inscribed on a sheet of paper. It follows that, in order to bring the proportions of the movement, the curve of which is to be recorded, within convenient proportions, it must either be enlarged or reduced.

Proportional Enlargement and Reduction of the Recorded Movement.—Very feeble movements, such as occur in living organs, and such as physiologists wish to understand, usually have to be immensely enlarged. This can be effected by levers with needles fixed to

has traversed a distance of five hectometres at a uniform rate. This rate is maintained for two minutes longer (section B), then a stoppage occurs for one minute, after which the moving body again advances at an accelerated pace until the tenth minute. This speed of two hectometres a minute is maintained up till the end of the eleventh minute, when it again gives place to a slower movement of three hectometres in four minutes. This is maintained during section D and part of E, until the twenty-first minute, at which a period of rest occurs. This stop of three minutes, which is continued during section F, is followed by another period of uniform movement during which the speed is a little more than 100 metres per minute.

their extremities. It is in this way that the arterial pulse, as it alternately raises and lowers the lever, demonstrates in different patients the condition of the circulation.* When a movement is on too large a scale to be recorded in its actual size, it must be

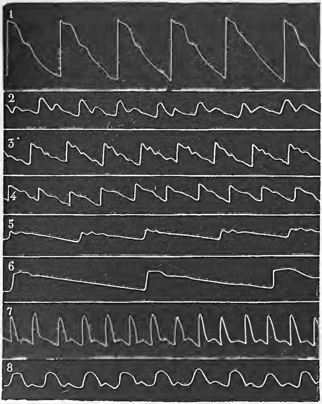

FIG. 28.—Enlarged tracings of the pulse in different diseases.

reduced before transmission to the recording needle. There are several ways of doing this, the following are the most usual methods. The movement can be reduced by allowing it to act on the longer arm of a lever, while the writing needle is placed on the shorter.

* See *The Circulation*. Paris, G. Masson, 1881.

The relationship which obtains between the lengths of the two arms determines the degree to which the movement is reduced. A movement can be uniformly reduced by means of an indiarubber thread; this is a convenient method, and quite reliable enough for most purposes.*

Fig. 29.—Proportional reduction of a movement by means of an indiarubber thread.

Let $c\ b$ (Fig. 29) be an elastic thread as nearly homogeneous as possible. Under the influence of traction it will become equally extended throughout its length. Let us make fast one of its extremities, c, by means of a nail, for instance. If we exercise traction at the other end, b, so as to bring it to b', the point a near to c will only travel the short distance aa'. If we have fixed the tracing needle at this point, it will record on the revolving cylinder a curve, the amplitude of which will be to that of the real movement as the length of the thread ca is to the length cb.

But when the movement has to be immensely reduced, as happens when the path of a body moving through several kilometres has to be traced on a strip of paper a few centimetres in length, the movement has to be reduced by means of a mechanical arrangement of wheels.

A system of small pinions and large wheels will effect this object; in fact, as we know, it will indefinitely reduce the amplitude of any movement. We had recourse to this method when we obtained the

* This method of reducing the curve by means of an elastic thread was thought of by Admiral Paris and his son. It was made use of in their apparatus described under the name of "Wave Tracers." —*Maritime and Colonial Review*, June, 1867.

curve of movement presented in Fig. 27. The instrument employed in this experiment is applicable for registering the progress of all kinds of machines. It is called an "Odograph."

The Odograph. — Fig. 30 represents a pedestrian

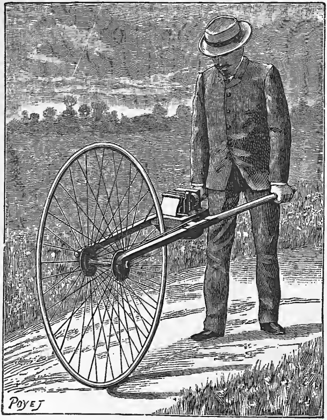

FIG. 30.—Pedestrian pushing an *odograph* in front of him.

pushing before him a light species of wheelbarrow. The track of the wheel upon the ground represents the distance traversed. The wheel of the barrow, by a system of reducing wheels, controls the movement of a strip of paper. Further, a tracing needle worked by a clock moves across the paper at any desired rate. A

time-curve of the distance traversed results from the combination of these two movements. Figs. 31 and 32 show the details of the apparatus. A strip of paper, the length of which is about one metre, passes between cylindrical rollers which advance it a distance proportional to the space traversed by the moving

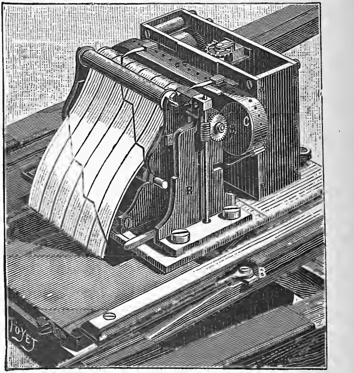

FIG. 31.—Details of the odograph. The strip of paper, which has already received a tracing of progression and rest, can be clearly seen in position. One needle has completed its journey, and a second, in its turn, is just about to commence. The needles, to the number of five, are arranged at a distance of six centimetres from one another, along a steel band which passes round the two rollers G by means of clockwork. At B can be seen the extremity of the shaft which imparts the movement to the rollers.

body. Each revolution of the wheel, representing a distance of three metres, will advance the wheel of the cylindrical rollers through a distance of one cog. This is effected by means of a crank which runs along one of the handles of the wheelbarrow. During this time

the strip of paper will have progressed a very short distance, 0·1 millimetre for instance. It will have completely passed through the rollers at the end of a run of 30 kilometres. The needle, which writes on the paper, is made of brass, and the paper itself is coated with a layer of white zinc, and called "*papier couché*," in the

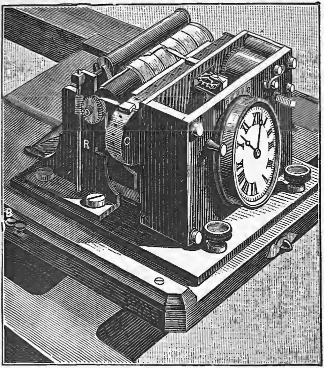

FIG. 32.—The instrument is seen obliquely from behind. The dial of the clock is visible. The strip of paper is in position between the rollers, and the needle is in the act of tracing. The teeth of the comb have already imprinted hourly subdivisions on the paper. At B the end of the shaft acts by means of a clapper on a ratchet-wheel, which in its turn controls the movement of the rollers by means of an endless screw.

trade. On this latter the brass leaves a very fine and clearly defined track. It never wears out like a pencil, neither does it require ink like a pen. To obtain a curve of the movement, the needle must have imparted to it a uniform motion by means of clockwork, and it

must traverse the width of the paper in one hour. Besides this, as the strip of paper is drawn through the rollers, it passes beneath a comb, which registers equidistant lines along the length of the paper; the distance between two teeth corresponds to a duration of ten minutes. This greatly facilitates the reading of the distance traversed in a particular time. Thus during every hour the needle traces a section of a curve analogous to those in Fig. 27, and which are distinguished in order by the letters A, B, C, — F, because the needle takes exactly one hour to cross the width of the paper. As soon as the first curve has been registered another one is commenced, because a second needle in turn begins to register, and at the third hour another needle, and so on indefinitely during the whole of the journey.* When the strip of paper ceases to advance, during periods of rest, the clock nevertheless continues to move the needle, and the latter describes a straight line at right angles to the long axis of the paper. This way of registering movement is identical with that which was designed by Ibry. We believe that odography could, with a few special modifications, be applied for registering the progress of a railway train. A novel arrangement of pneumatic tubes can transmit each revolution of the wheels of the engine to the mechanism of the cylindrical rollers, and thus an odograph can be placed in each compartment, and supply continuous information of the progress of the train. Thanks to the kindness of M. Millet, chief engineer of the locomotive department on the Southern Railway (Chemin de fer du Midi), we were able to try the effect of the odograph on express trains running from Dax to Bordeaux, and *vice versâ.* Fig. 33 shows in column A

* The needles are driven by an endless steel band controlled by the clock.

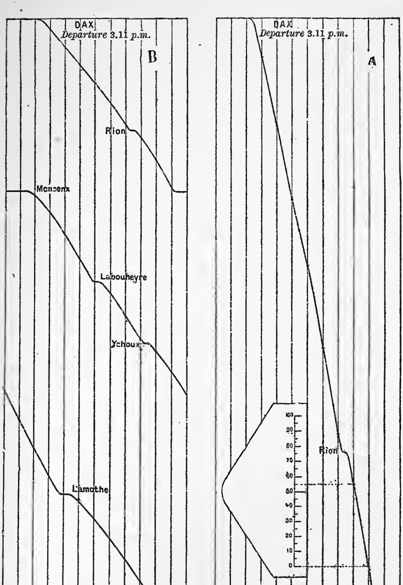

FIG. 33.—Two odographic charts expressing, according to different scales, the advance of a fast train.

a section of the original chart taken on one of these journeys between Dax and Moncenx. To measure from moment to moment the rate of travelling, a small divided scale can be applied to the corresponding part of the diagram. By means of this scale we can measure the length of any portion of the curve, which corresponds to the distance traversed in ten minutes. In this case it can be seen that the speed was 55 kilometres per hour. These charts are exactly like those employed by railway companies; the method of expressing periods of progression and rest is the same throughout, the only difference is, that Ibry's charts were theoretical, *i.e.* the speed of the trains is supposed to be uniform, and is represented by straight lines, and in ours the actual speed is experimentally found, and expressed by variations more or less pronounced. It can be seen that from Dax to Rion, and from Rion to Moncenx, the line is not straight but slightly curved, which means that there is a slight variation in the speed. It is generally immediately before, or immediately after, a stoppage that these variations are noticeable. At the moment that the train comes to a stop, the curve suddenly changes its direction, which indicates that under the influence of the brake there is a rapid transition from a high rate of speed to a condition of rest. On the contrary, at the moment of departure, the curve describes a parabola, which indicates how gradual is the acceleration, and how slowly the train gets up speed. The movement of the paper must be considerably slowed down, if we want to inscribe all the phases of a long journey within the limits of a single sheet of paper. Column B was obtained in this way, and on it is registered a journey from Dax to Bordeaux, representing a distance of 60 kilometres.

In odography the movement of the paper should be

regulated to suit the average speed of the conveyance the movement of which is to be ascertained, be it carriage, locomotive, or boat, etc.* Wide as is the range of movements capable of being recorded by mechanical means, nevertheless there are, as we remarked before, cases in which this method ceases to be applicable. It will be seen how valuable the employment of photography becomes in cases of this kind.

Photography of the Movements of Lippmann's Electrometer.—In 1877, our colleague and friend Lippmann had just invented his capillary electrometer, an instrument so marvellously sensitive that it was capable of registering the slightest electrical variation that occurred in living tissues. But for this purpose it was necessary to make this electrometer a recording instrument. This was managed by means of photography.

As the column of the electrometer is exceedingly fine, the movements must be observed under the microscope.

This column presents totally different appearances under different conditions of illumination; on a light background it appears as a dark line; on a dark background, when illuminated from the sides, it stands out as a very bright line. This column is seen to elongate and contract according to the direction and the intensity of the current acting upon it. By receiving its image on a photographic plate a very intense black line will be obtained. If the sensitive plate is moved at a uniform rate at right angles to the axis of the column, all its variations in length will be apparent in the image.

The effect of moving the plate is that the image of the column is no longer a simple line; it is spread out in the form of a band, the sinuous border of which

* For the details of the employment of odography, see *La Nature*, No. 278, September 28, 1878.

corresponds to the variations in the length of the column of mercury.

To illuminate the column of this instrument, we used a series of flashes from an induction coil furnished with a condenser. This intermittent illumination disturbed the continuity of the images, and thus a series of bright lines of unequal length was produced.

By this means tracings can be obtained to demonstrate the electrical changes in the hearts of tortoises or frogs, as they occur respectively during the periods of systole and diastole.

The sinuous border representing the summit of the column of mercury in such a tracing has a very close resemblance to the curve obtained by mechanically registering the actual movements of the heart during its various phases. The heart, like all other muscular structures, shows changes in its electrical condition, according as it is contracted or relaxed.

Determination by Means of Chronophotography of the Movement executed by a Falling Body.—In the study of movement, photography has the advantage of not being obliged to borrow any motive power from the object observed. The following experiment may be made. A black-velvet curtain may be hung vertically so as to form a dark screen, in front of which a white ball, lit up by the sun's rays, is allowed to fall. A divided scale is placed vertically in front of the dark background, to measure the distance traversed. A chronometric dial is used to measure the intervals between the successive images.

When the circular diaphragm has acquired the desired velocity, an assistant pulls the string and the ball falls. The photographic plate receives a series of images of this ball, showing the positions it occupies at each successive exposure. In this way all the necessary elements are obtained for determining "the

laws of motion." In order to make it more easy to take measurements from this photograph, the original plate is enlarged, and the different positions of the falling body are obtained on a convenient scale. Let us draw a horizontal tangent to the ball in each of its positions. The distances fallen during the various periods since the commencement of the fall will then be seen in series, and it will be observed that these distances increase as the square of the time. For instance, the distance traversed during the second period of fall, that is to say, after the second exposure, is four times as much as that which was traversed in the first period.

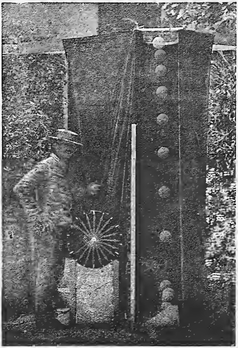

FIG. 34.—Photography of the movement of a falling body.

If one wishes to construct a time-curve of the distance traversed, the sheet of paper should be divided by vertical lines at equal distances. At the intersections of each of these lines with the horizontal tangents a mark is made (a dot in the centre of a circle). The curve E, which joins all of these marks, is a parabola, and represents the time-curve of a body moving at an uniformly accelerated rate.

The curve of velocity can be constructed by marking

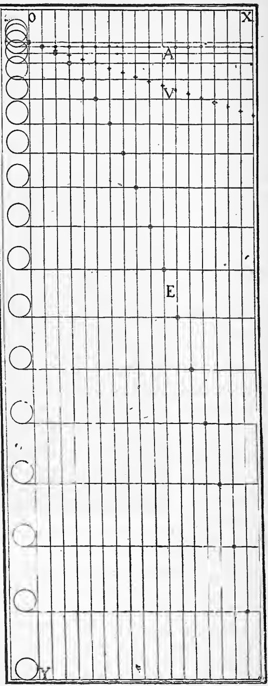

FIG. 35.—Curves of the movement of a falling body.

off from each time-division a distance which represents the space traversed by the ball in the corresponding interval of time. The small crosses mark the lengths of such a series of ordinates. Taken together they form the line V, which is the curve of velocity. Such a line is a straight one, but obliquely inclined, and expresses a velocity of uniform increment.

Finally, the curve of acceleration is obtained by marking off on the ordinates, under each of the time-divisions, the excess of velocity of each period over and above that of the one which precedes it, that is to say, the excess of the second over the first, and the third over the second; in other words, the increment of velocity, or acceleration, in a series of time intervals. A large black dot marks the length of each of these ordinates; the dots united together by the line A constitute a straight horizontal line showing the acceleration was uniform.*

In constructing these figures, the unit of time was represented as any interval. This method answers very well in comparing the relative degrees of speed and acceleration; but to ascertain the exact degree, these indefinite intervals must represent a second, the recognized unit of time.

The chronometric dial provides us with the means of doing this in the same manner as the divided scale measured in meters and fractions of meters the space traversed by a falling body. Thus chronophotography provides us with the means of constructing the curves of movement.

* On account of a mistake in the diagram (Fig. 35), the degree of acceleration is half what it ought to be.

CHAPTER IV

CHRONOPHOTOGRAPHY ON FIXED PLATES

SUMMARY.—Object of chronophotography; principles of the method: measurement of time and space—Influence of the extent of surface covered by the object which is to be photographed; influence of the rate of movement—Geometrical chronophotography—Stereoscopic chronophotography—Method of multiplying the number of images without producing confusion—Alternating images—Separation of the images on the photographic plate; separation by moving the apparatus—Separation by employing a revolving mirror.

SINCE the object of chronophotography is to determine with exactitude the characters of a movement, such a method ought to represent the different positions in space occupied by a moving object, *i.e.* its trajectory, as well as define the various positions of this body on the trajectory at any particular moment.

Let us suppose that an ordinary photographic camera is directed towards a dark background, that the lens is uncovered, and that a ball, brightly illuminated by the sun, is thrown across the field of the objective. During its passage this ball leaves an impression on various parts of the sensitized plate, and on examining the plate there is found a continuous curved line which exactly represents the path taken by the luminous ball (upper curve, Fig. 36).

If we repeat this experiment, but only admit light into the dark chamber in an intermittent fashion, and

at regular intervals of time, an interrupted trajectory will be obtained (lower curve, Fig. 36). This represents the successive positions assumed by the moving object at each moment when light is admitted. This is the chronophotographic trajectory. In this method the intervals of time separating two images are of constant and known duration.

To obtain the best possible results, the object must be brightly illuminated and the background absolutely dark. The duration of the exposure must be very brief, in order that the object may not move an appreciable distance during a single admission of light.

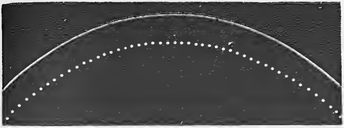

FIG. 36.—Simple trajectory and chronophotographic trajectory of a bright ball moving in front of a dark background.

The original form of the chronophotographic apparatus was very simple. It consisted of an ordinary camera and lens. Within the body of the camera, in front of the plate, a fenestrated diaphragm was fixed. This rotated at a perfectly uniform rate by means of a crank and regulator. The sensitized plate was held in a frame and fixed in a position so that the object was focussed accurately upon it. As each slit in the diaphragm came into position, the plate received an impression of the illuminated object, representing the actual form and position of the object at that particular moment. Now, as the object became displaced between successive exposures, a series of impressions was obtained exactly corresponding to the shape and position

of the object in the various phases of motion. The interval between each image was exactly $\frac{1}{10}$ of a second, and the duration of the exposure $\frac{1}{500}$ of a second. A metre rule with very clearly defined divisions was placed in front of the screen, and in the same plane as the object. The image of this rule reproduced on the sensitized plate served as a scale to measure the real size of the object, and the spaces traversed during each period of $\frac{1}{10}$ of a second.

Instead of depending on the absolute regularity of the movement of the diaphragm as a means of measuring the time relations, it would be better in experiments requiring great accuracy to make use of the chronometric dial (Chap. I., Fig. 12). Thus in the experiments on falling bodies described on page 51, the intervals of time between two successive exposures were measured by the angular distance through which the needle moved between two successive images. This proceeding, like that in which the tuning-fork is employed as a mechanical means of registering the rate of movement of the paper, permits of the diaphragm revolving at any speed required. The degree of speed can always be ascertained by referring to the position of the needle on the dial.

As for the measurement of space, the image of a divided scale serves, as we said, for measuring the various distances on the photographic plate.

But, since all measurements made from a reduced scale necessitate a series of calculations before the real dimensions are ascertained, it is very desirable to find some means of avoiding these tedious calculations. This may be done by enlarging the images, by means of a projection lantern, until the object assumes its actual dimensions, *i.e.* until the measuring scale on the screen appears to be exactly one metre in length. In this case all the dimensions of the image can be directly

measured. Such chronophotographic pictures contain the two necessary elements for understanding a movement, namely, a notion of space as well as that of time; nevertheless, as we shall see, it is often difficult to harmonize two such incompatible notions without having recourse to certain expedients.

Influence of the Extent of Surface covered by the Moving Object.—If the object under observation covers only a small surface in the direction of movement, a large number of images may be obtained without superposition or confusion, as, indeed, we noticed in the case

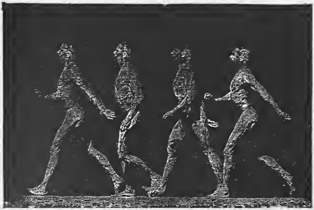

FIG. 37.—A man walking. Chronophotography on a fixed plate.

of the moving ball. As far, then, as time is concerned we have a very complete picture, whereas that of space is very restricted.

Now, if we take a series of images of a man walking, the question of space becomes a most complicated one. Each image must be spread over a considerable surface if it is to show the various positions assumed by the head, arms and legs. Now, the larger the space covered by the image, the smaller must be the number that can be taken on one plate without superposition and confusion. With a large animal, a horse for instance,

the number of images has to be very limited, for the length of each, measured in the direction of movement, is so great that they readily overlap, as in Fig. 38.

FIG. 38.—Arab horse at a gallop. The large surface covered by each image causes almost complete superposition.

Influence of the Rate of Movement.—In different speeds of translation, the number of images which can be taken in a given time without producing confusion, increases as the former become greater. This may be proved by comparing a series of images of a runner (Fig. 39) with those of a man merely walking (Fig. 37).

FIG. 39.—A man running. Chronophotography on a fixed plate.

The figures of the runner are much further apart, although the frequency of exposure is the same in both cases. If the runner were to come to a standstill, the images would become superimposed. Sometimes such

a superposition of images can be put to practical use. Thus it gives greater intensity to those images which represent the movements of least rapidity. One of the very first applications of photography to the study of movement was suggested by Messrs. Onimus and Martin, in the year 1865. These investigators exposed the heart of a living animal, and took a photograph of it by leaving the lens permanently uncovered. The photograph was found to have a double outline representing the two extreme positions of contraction and

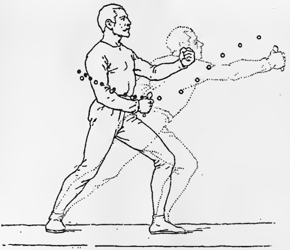

FIG. 40.—A boxer represented in the two extreme positions of a movement.

dilatation. At these two periods the heart remains momentarily motionless, and its configuration is imparted to the sensitized plate, whereas no clear impression is left of it during the intermediate phases of motion.

Mr. Demeny had recourse to this method, which had fallen into unwarranted oblivion, and with which even he himself was previously unfamiliar. In studying physical exercises, he took the photograph of a man in the act of boxing in front of a dark screen.

His photograph showed two particular attitudes clearly defined, and from them Fig. 40 was produced; the latter shows the boxer preparing for a movement, and his position immediately after completing it. The intermediate phases of movement were so rapid that they left no appreciable impression on the plate.

Fig. 41.—Man dressed in black, with white lines and points for the chronophotographic study of the movement of the important parts of the body.

Geometrical Chronophotography.—This confusion from the superposition of images sets a limit to the application of chronophotography on fixed plates, yet in many cases, by means of certain appliances, this difficulty may be overcome. The most obvious method

consists in artificially reducing the surface of the object under observation. Such parts of the object as are not wanted in the photograph are blackened and thus rendered invisible; on the other hand, those portions, the movements of which are to be studied, are picked out in white. Thus a man dressed in black velvet (Fig. 41), with bright stripes and spots on his limbs, is reproduced in the photograph as a system of white lines, which indicates the various positions assumed by the limbs. In the diagram thus obtained

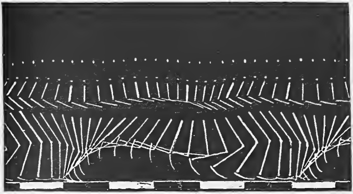

Fig. 42.—Images of a runner reduced to a system of bright lines for representing the position of his limbs. (Geometrical chronophotography.)

(Fig. 42), the number of images may be considerable, and the notion of time very complete, while that of space has been voluntarily limited to what was strictly necessary.

Stereoscopic Chronophotography. — In Chapter II. we discussed the method of obtaining stereoscopic pictures of figures described by straight or curved lines moving in space. A series of separate images was thus obtained, that is to say, they were produced by intermittent exposure of the objective. This was done with the double object of explaining the method of producing figures in relief, and of showing the

successive positions occupied by the line which engendered them. Now, if the intervals between the exposures are precisely equal, we have an example of stereoscopic chronophotography, and consequently a complete expression of the movement. This method is applicable in a great many cases in which we want to know whether the moving object moves in one plane only or in three.

Method of multiplying the Number of Images without producing Confusion.—The applications of chronophotography are, as we have seen, limited by interference from superposition and consequent confusion. Now, the larger the space covered by the object, and the slower the movement, the sooner does superposition occur. Thus, if the space is large and the movement slow, recourse must be had to certain measures, if we want to obtain a photograph of the various positions occupied in space.

One method consists in taking alternating images, another in separating the images on the plate by making them fall on different parts.

Alternating Images.—To obtain these, a stereoscopic apparatus with two lenses is employed, both of which are controlled by the same diaphragm. Such a diaphragm should be circular, and contain only one slit, which, as it rotates, alternately admits the light first by the right and then by the left lens. Two series of images will be thus obtained, which lie in two parallel lines. The upper series corresponds to the odd numbers, and the lower to the even numbers, as is shown below—

```
1   3   5   7   9   .
  2   4   6   8   10
```

In this way Fig. 43 was obtained, which shows the various positions of the wings as assumed by a seagull during flight.

Only five different positions can be represented in a single series without confusion. Now, thanks to the two series, which are the complements of each other, the number of images is doubled, and the succession of movements represented by them can be followed by passing alternately from the odd to the even number in the natural order, as is indicated by the small arrows in the diagram.

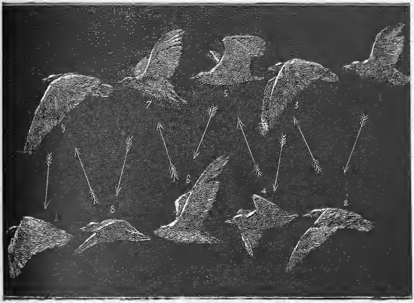

FIG. 43.—Alternating images for multiplying the number of positions afforded by chronophotography.

It is almost unnecessary to add that these images do not constitute a stereoscopic series, for they are taken successively, and the single slit of the diaphragm never exposes more than one of the two photographic plates.

Separation of the Images on the Photographic Plate.—When the object, of which successive images are to be taken, confines its movements to one particular spot, confusion and superposition are bound to occur. This

difficulty, however, can be overcome by a variety of expedients, one of which is already known to us, and which depends on the horizontal and forward movement of the photographic plate.

In speaking of the photographic registration of the variation of Lippmann's electrometer, we showed how successive images of the illuminated column of mercury formed a continuous series, owing to the onward movement of the plate. This mode of representing the various phases of electrical variation is entirely comparable to the mechanical registration of a movement by means of a needle which traces its record on a moving strip of paper. This kind of separation would be applicable in a great number of cases if it did not require a special and rather complicated apparatus, namely, that of a movable slide and a clockwork motor. But with an ordinary apparatus a similar separation can be obtained by imparting an onward movement to the image itself while the photographic plate remains in position. In order to effect this, a rotatory movement round its own axis must be communicated to the apparatus itself between the periods of exposure. The principal optical axis of the objective is thus displaced in a horizontal plane; and the image of a man standing in front of the dark screen will consequently be displaced in a corresponding direction on the plate itself. If this man executes certain movements in the same spot, thus constituting a variety of attitudes, or if he advances excessively slowly, his successive attitudes, instead of being confused and superimposed, will constitute a series of disconnected images, ranged side by side, as if he were moving at a moderate pace in a horizontal direction in front of the dark screen.

But it may be urged that the conception of space

is false, because a variety of attitudes on the same spot are reproduced in the photograph as if they were onward movements. The real position of each movement must be located in the diagram. This can be done in the following way:—By the side of a man jumping about on the same spot, or walking slowly, a white and perfectly motionless object is placed just in front of the dark background. The images of this object will be arranged in a consecutive series on the

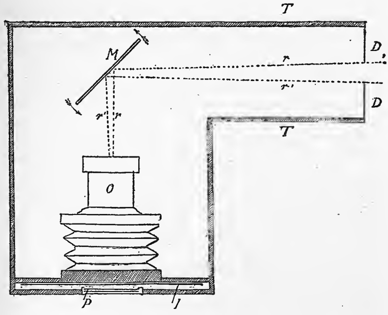

FIG. 44.—Rotating mirror for separating the images of an object which moves too slowly.

plate. Now, as it is known that these positions correspond to a fixed point, they serve as a means of estimating the real positions occupied by the man at the time of each exposure. Such a movement imparted to the apparatus is a very simple means of obtaining a consecutive series of chronophotographic

images, but it is difficult to ensure perfect regularity of movement.*

A better method of producing the same result consists in reflecting the image of the object by means of a revolving mirror. The image thus becomes deflected before it enters the camera. The mirror, silvered by Foucault's method, rotates on a vertical axis, and by means of clockwork it is easy to ensure a uniform movement. Any speed that is desired can be obtained.

By these different ways of separating the image, the range of chronophotography on fixed plates can be considerably extended. For thus we are enabled to record movements executed on the same spot, or of extreme degrees of slowness. At the same time the method ceases to be applicable when the duration of the movement is greatly prolonged, when a large number of images are required, or when the dimensions of the plate will not contain the images. Neither is it applicable when the moving object is dark and the background light. Recourse must then be had to a new method. This is chronophotography on a moving plate; it will be described further on.

* Another inconvenience presented by this method is that there is a risk of the apparatus itself introducing a source of error. For the circular diaphragm rotating at a great rate tends to preserve its own plane of rotation, and consequently to become distorted when exposed to sudden movement.

CHAPTER V

DESCRIPTION OF THE APPARATUS

SUMMARY.—Construction of the apparatus—Slide, object-glass, circular diaphragms—Erection of the dark background at the physiological station—Dark background for photographing objects in water—Photography of light objects in darkness or in a red light—Colour of objects, and way of illuminating them—Disposition and preparation of the dark field—Choice of the object-glass—Focussing—How to take the photographs.

Chronophotographic Apparatus.—An ordinary photographic camera can be used in chronophotography, provided that it is furnished with a diaphragm which gives very short periods of exposure at regular intervals of time. For this purpose the simplest arrangement, and the one we originally employed, is a disc which is provided with small foramina, and which revolves in a slot cut in the mounting of the objective. The disc is made to revolve by a system of pulleys and a continuous chain worked by clockwork and controlled by a good regulator. But there is a difficulty in combining a clockwork motor and a photographic camera, as well as in changing the disc from time to time, as the rate and frequency of the exposures may require, and this has induced us to abandon so clumsy an apparatus. We determined to construct a special instrument at once portable and capable of being regulated as desired. Such an arrangement is the more necessary because there are

certain movements which cannot be chronophotographed on a fixed plate, and which must be represented as a series on a long photographic film, which can be unrolled at the back of the camera.

The chronophotographic camera, as shown in Fig. 45, meets all the above requirements; but, for the present, we must be content to describe only those parts which are necessary for taking photographs on fixed plates. The apparatus consists of two halves united by bellows. The hinder part slides on a rail

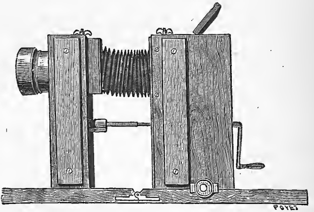

FIG. 45.—Arrangement of an apparatus adapted for all the purposes of chronophotography (scale $\frac{1}{10}$).

by means of a screw-rack for convenience in focussing, and into this part the dark slides are introduced. The objective is contained in a box (Fig. 46) which is cleft beneath, and accurately fitted so as to slide into the front part of the apparatus. The cleft under the box is continued into the mounting of the objective, and thus divides the object-glass perpendicularly to its principal optical axis, and allows room for the fenestrated diaphragms. The latter by their revolutions regulate the intermittent exposures. One end of the bellows fits into the box containing the objective, while the other, attached to the hinder part, com-

municates by means of a large opening with the frame,

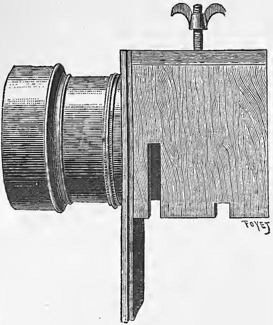

FIG. 46.—Objective mounted in a sliding box. Below can be seen the opening for the passage of the circular diaphragms.

which contains both the ground-glass plate (Fig. 47) and the negative (Fig. 50). The only parts which call

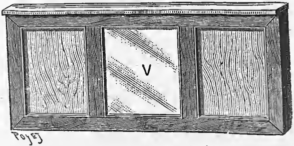

FIG. 47.—Frame with ground glass for focussing in chronophotography on fixed plates.

for special description are the circular diaphragms, and the shaft which serves to communicate movement to

them. These diaphragms rotate in opposite directions, and as two foramina pass each other an exposure occurs, and the plate is illuminated. By this arrangement we can employ discs of small size, and consequently greatly reduce the total dimensions of the apparatus. In fact, the dimensions need not exceed the size of an ordinary (24 × 30) camera. The shaft, which determines the revolution of the diaphragms, receives its own motion from wheels, which are worked

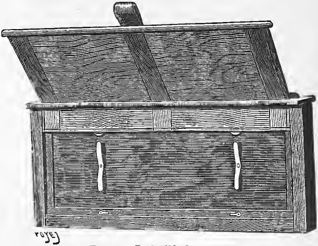

Fig. 48.—Dark slide for negative.

by a crank. At present, however, we have no space for a detailed description.

Now, in focussing, the position of the slide must vary considerably, and the two parts of the apparatus must be more or less separated from one another. The shaft must therefore be able to accommodate itself to these changes in distance, and for this reason is composed of square tubes, which slide one within the other with what is technically called a telescopic action.

Erection of a Dark Background for Chronophotography.—The principles of chronophotography on

fixed plates demand that the objects, of which the movements are to be studied, should be the only ones to appear on the sensitized plate, and that the background should not throw a single ray of light into the apparatus.

A black velvet curtain may be used for this purpose, provided that the sun does not shine directly upon it, for all substances, however dark their colour, reflect a certain amount of light when strongly illuminated.

Chevreul pointed out that the only means of obtaining absolute darkness was to blacken the inside of a box, and make a hole in one of its sides. By the side of this dark hole all black material illuminated by the sun appears to be coloured. The nearest approach we have been able to make to these ideal conditions of Chevreul was by constructing a dark and capacious shed (Fig. 49) at the Physiological Station,* the interior of which has been painted black, and by hanging a black velvet curtain at the back. The opening of the shed is eleven metres long by four in height. This opening is so situated that the sun cannot penetrate into the interior.

* This establishment, by permission of General Assembly and the Municipal Council of Paris, was set up in Princes Park (Park des Princes). Here it is possible to carry out certain researches which would be impracticable in laboratories of the ordinary kind. Such a field for research exists as yet nowhere else. There is a long circular track, perfectly horizontal, and five hundred metres in circumference; on this the ordinary paces of men and large animals can be studied. By means of a dark background, it is possible to apply chronophotography on fixed plates to the analysis of long-continued movements. A background, uniformly illuminated, and of even surface, offers facilities for chronophotography on moving films. Registering dynamometers, spirometers, pedometers, and various apparatus for the measurement of objects under observation are devoted to the study of human locomotion. In addition, pneumographs, sphygmographs, and cardiographs enable the investigator to study the effect of athletic exercises on the functions of organic life, and to follow step by step the improvement under training. Finally, there is an enclosure, where various kinds of animals can be reared in liberty, and where their normal and modified locomotion can be studied at pleasure.

In front of the opening there is a track paved with blackened wood, along which, when it is necessary to analyze any particular kind of movement, the man or animal is made to walk. Theoretically, an indefinite number of images may be taken in front of a dark background without any impressions of outside objects appearing on the plate. Practically, when several hundred successive images of a luminous object have

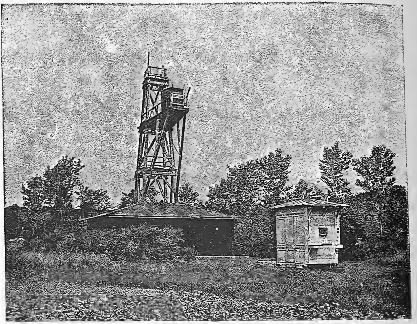

Fig. 49.—Arrangement of the dark background at the Physiological Station. In front of it there is a small chamber running on rails for keeping the apparatus. Above the dark background a framework is arranged for holding the camera at a distance of 12 metres, when it is necessary to photograph from above.

been taken, the plate sometimes appears "fogged" in the areas which correspond to the dark background. This proves that a small quantity of light emanates from this source. The appearance of "fogging" curtails the duration of development, and diminishes the intensity of the image. The slightest reflection

of light from the dark background must be prevented, because, however feeble may be the light from this source, since it affects the sensitized plate every time the objective is uncovered, the ultimate sum of these insignificant effects will finally become appreciable.

One of the important factors in obtaining a good negative is a pure atmosphere. Particles of dust floating in the air, when illuminated by the sun, form a sort of luminous haze, which interferes with the clearness of the photographic field. The effect is very noticeable when a horse at a quick pace passes along the track which stretches in front of the background. The track should therefore be kept moist, the soil in the neighbourhood should be turfed, and the inside of the shed kept scrupulously clean. It often happens, however, that the rays of the sun, although they do not penetrate directly into the interior of the shed, nevertheless impinge on the ground which surrounds the entrance, and thus become reflected on to the velvet curtain; the darkness of the photographic field is in consequence considerably reduced. Even if the ground of the shed is composed of asphalte, it is as well to stretch a strip of velvet over those portions of it which are directly illuminated by the sun.*

In any case, the chances of light being reflected are minimized by reducing the opening of the shed to the smallest possible dimensions. It seldom happens that the range of movement under observation equals the whole length of the shed, which measures eleven metres in this dimension. Often, too, it is unnecessary to utilize the entire height of the opening, which measures four metres. This can be reduced by means of blinds and

* An arrangement which would be perfect, but of which the resources of the Physiological Station do not admit, would be to lower the level of the ground inside the shed, so as to make it impossible for sunlight to reach it.

black curtains to the smallest dimensions, thus augmenting the darkness.

The majority of experiments do not require such large backgrounds, and can be carried out quite easily under the best conditions.

A square box of 0·50 metre side, lined inside with black velvet, makes an excellent background, especially when the opening in the box is limited in size. In this way photographs can be taken of the movements of small animals, and, generally speaking, of all small objects. The photographs in Chapter II. were taken in front of a box of this kind. They show the figures described in space by a white thread moving in all three directions.

Dark Background for photographing Objects in Water.—For the study of the locomotion of fish, and of other movements taking place under water, the objects to be photographed must be themselves brightly illuminated, while their surroundings are in total darkness. For this purpose a rectangular tank with glass sides is placed in front of a dark background; the bottom of the tank is similarly made of glass, and through it the sunlight is allowed to enter after being reflected from a mirror set at an angle on the ground. This arrangement is shown in Fig. 50. Here it will be noticed that the glass tank forms part of an elliptical canal, so that the animals can move round and round, like horses at a circus. The canal is three-parts filled with water, and the transparent part is illuminated by means of an inclined mirror, which receives the sun's rays direct. The canal, mounted on a high table, is furnished with handles, so that it can be easily moved from place to place. It is set out in front of an open window, through which the sunlight can fall upon the inclined mirror. The apparatus is variously disposed according to the time of day, and the inclination of the

mirror so set that it reflects the sunlight vertically upwards through the tank. Thus illuminated, all objects floating in the water appear bright, but the water itself, if quite clear, is perfectly invisible. It only now remains to form a dark background by placing a black velvet curtain behind the transparent portion, and to prevent the entrance of any outside light. This is done by means of a light rectangular

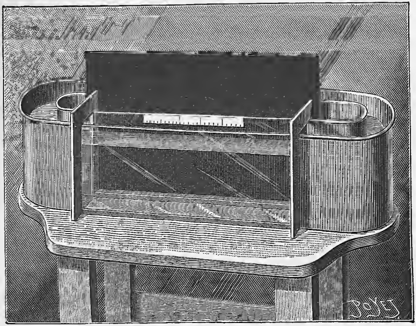

FIG. 50.—Dark background for the study of movements occurring in liquids.

framework, pyramidal in form, and covered with a black material. The base of the frame envelopes the glass tank, and the other end receives the object-glass. An opening made near the top allows the experimenter to watch what is going on in the water, and to seize an opportune moment for taking the photograph (Fig. 51).

Photography of Light Objects in Darkness or in a Red Light.—No dark background is needed at night-time,

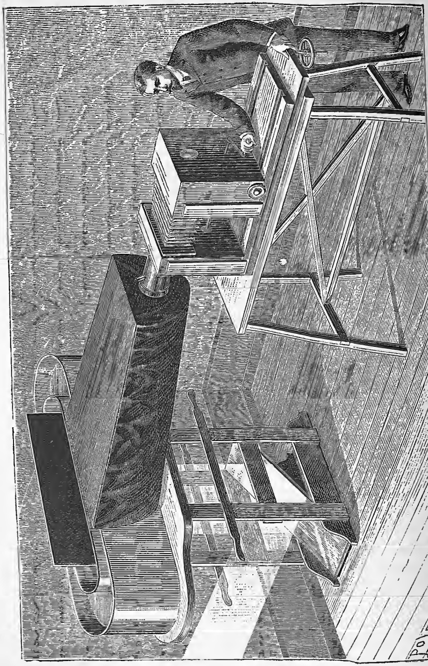

FIG. 51.—Arrangement of the experiment for studying movements in liquids.

or in a place illuminated by red light, provided that the object to be photographed is itself a luminous body, such, for instance, as an incandescent lamp; the latter gives excellent results.

L. Soret was the first to make use of this arrangement. At night, on the stage of a theatre, lighted only by a few red lanterns, he studied the movements of dancers, by fastening little incandescent lamps to their heads and feet. In this way Soret obtained some

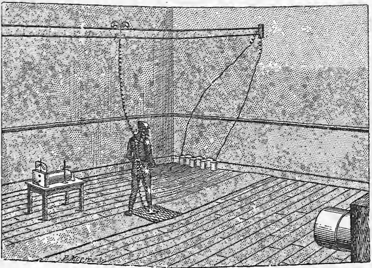

FIG. 52.—Arrangement employed by Messrs. Demeny and Quénu for studying (by means of chronophotography) abnormalities in walking.

very curious trajectories, in which the curves obtained showed a beautiful and regular interlacement.

Messrs. Demeny and Quénu similarly made use of incandescent lamps in analyzing, by means of chronophotography, the characteristic gaits of patients afflicted with various kinds of lameness.

A room in a hospital was provided with red windows (Fig. 52), a track was marked out on the floor for the patient to walk on, and the apparatus was placed at a suitable distance. Incandescent lamps were fixed

to the joints of the legs, to one of the shoulders, and to the head of the subject. These lamps were connected with the battery by means of a carriage, which ran along wire rails, and accommodated itself to the various movements. The negative obtained consisted of a series of bright spots corresponding to the successive positions of the different lamps. By connecting the points by straight lines the geometrical chronophotograph of the gait was obtained.*

The combined use of red illumination and the electric light has infinite variations. For instance, if one arranges a powerful electric search-light so that the beams are directed across a room illuminated by red light, only the objects shown up by the electric light will produce a reaction on the photographic plate.

Colour of Objects and Way of Illuminating them.—When the objects under observation are white, or of some colour that can be photographed, strong illumination is all that is necessary for obtaining good results, because, if the background against which they are projected is quite dark, by slightly prolonging the process of development the images are made to stand out quite clearly. When, however, the colour of the objects is difficult or impossible to photograph, it is necessary to colour them artificially.

* As it would be very difficult in this long succession of points to recognize those simultaneously formed, the following arrangement was designed: The diaphragm contained five fenestrations, and consequently produced five images for every complete revolution. Now, one of these fenestrations was made larger than the rest, and consequently the particular image produced by it was of greater intensity than the others on the plate, owing to the longer exposure. In such a negative one can see that in each series of spots every fifth spot is more accentuated than the intermediate ones. These are the main points which must be connected by straight lines, so as to represent in the diagram the axial position of the limbs at successive moments. As for the little intermediate points, they are not without their use, as by their degree of separation one can measure the rapidity of movement of the various joints.

In our attempts to represent, by chronophotographic means, the various changes in shape and appearance of an animal's heart, as occurring in the auricles and ventricles, we met this difficulty in its extreme form, since the red colour of the muscles and of the blood made no impression on the photographic plate.

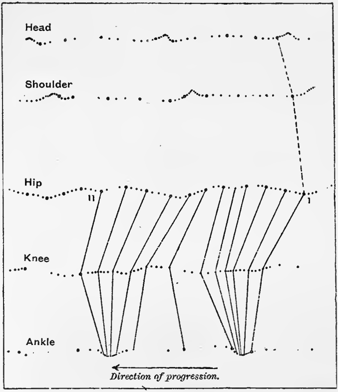

FIG. 53.—Extent of the movements of the legs obtained by Messrs. Demeny and Quénu in a dark room.

By painting the surface of the heart with a solution of Chinese white we have found it possible to take a photograph of it, and we have obtained excellent results with very short exposures. We need say but little about the best conditions for illuminating the contour of objects. In this respect photographers

have acquired such skill that we can do no better than borrow their methods.

Generally speaking, objects should be directly illuminated, but the dark background often makes lateral illumination necessary. When this latter means is employed, the contour of certain parts of the object may be very well defined, but others may be too much in the shade. This can be rectified by employing reflectors properly inclined. To sum up, the problem of illumination must be solved in a variety of ways, but it is chiefly of importance in those rarer cases, in which artistic effects are the chief aim.

Disposition and Preparation of the Dark Field.—The breadth which one must give to the background depends upon the extent of the movement, the various phases of which we want to follow. The opening must correspond to the amplitude of the movement in such a way that the least possible amount of light may enter the box. In the same plane as that on which the movement is to take place, a metre scale must be fixed, and, if there is room, the chronometric dial also.

Lastly, the photographic apparatus must be placed just far enough off for the sensitized surface to correspond to the limits of the background. But to regulate this, the limits of the background must be visible on the ground-glass plate, and so they should be indicated by placing on them bright-coloured strips, or other striking objects.

Choice of the Objective.—When the observed movement is strictly confined to one plane, any sort of objective can be employed, but it must be placed at such a distance that the image on the ground-glass plate assumes the proportions required. In this case it is better to use an objective of short focal length, since it admits a larger quantity of light. Under

other conditions, the use of objectives of short focal length is less convenient.

If the object to be photographed has any depth, it will appear at different points of its course in different perspectives, that is to say, when the observer is only a short distance off. But this difference in perspective

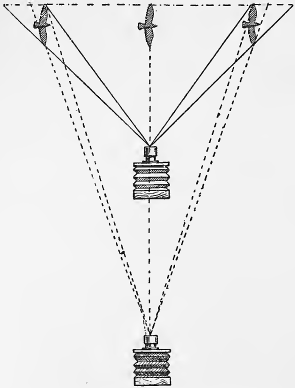

FIG. 54.—Changes which occur in the perspective of a moving animal according to the distance off at which the photographic apparatus is placed.

becomes less as the observer moves further away from the object. To take an example: Suppose a bird flies in front of a camera, and that we observe its positions, when it is to the left of the camera, when it is exactly opposite, and when it is to right (Fig. 54). In the first case the bird will be seen from the front, in the

second exactly from the side, and in the third from behind. These differences in perspective are less appreciable if the apparatus is removed further off, and the respective images become more easy to compare and to measure. But by moving the camera further away the images become smaller, and hence it is necessary to use an objective of greater focal length in order to obtain large enough images. We need say no more on this subject, since text-books on photography give most exact directions.

Focussing.—The object is brought into focus on the ground-glass plate in the slide (Fig. 47). The apertures of the two diaphragms must be made to coincide by turning their axes with the hand, and the image is seen through an opening situated at the back of the apparatus above the crank.*

How to take the Photograph.—Just as the aperture of the box is kept within strictly necessary limits, so too is the length of the exposure reduced as much as possible. If the sensitized plate be unnecessarily exposed before or after the end of the phenomenon, the intermittent exposure of the objective will allow access to the plate of small quantities of light, which tend to cause "fogging." This inconvenience can be avoided by placing in front of the objective a special diaphragm, of the kind which is worked by pressing an indiarubber ball with the hand. This anterior diaphragm, when shut, makes it possible to open the shutter of the dark slide, to place the apparatus in order, and prepare for the experiment, the sensitized plate being meanwhile in darkness.

At the moment the phenomenon commences, the

* This portion of the posterior part of the apparatus contains a special chamber adapted for photographing upon a moving film, which will be mentioned later. It is through this chamber that the image can be seen upon the ground-glass plate.

indiarubber ball is pressed, the anterior diaphragm opens, and the process begins. As soon as the phenomenon is over, the anterior diaphragm is again shut, and there is time to close the dark slide without any risk of the plate being exposed to detrimental illumination.

CHAPTER VI

APPLICATIONS OF CHRONOPHOTOGRAPHY TO MECHANICS

SUMMARY.—Bodies falling in air—Ballistic experiments—The resistance of the air to surfaces variously inclined—Applications of chronophotography to hydrodynamics—Fluid veins; changes in shape of fluid waves; intrinsic movements of fluid waves—Currents and eddies—Influence of the shape of bodies placed in currents—Oscillations and vibrations—Rolling of ships—Vibrations of metal bridges.

Bodies falling in Air.—To determine the movement of a falling body is one of the most difficult problems in dynamics. It may be said that Galileo's classical experiment was the origin of all experimental mechanics, for it taught us that a force could be measured by the motion it imparted to a material body.

Motion which is of uniform acceleration implies the absence of resistance; but when a body falls through the air, the resistance of the latter modifies the law of motion: it increases as the square of the velocity, and finally becomes equal to the force of gravity itself. At that moment the fall becomes uniform, that is to say, the resistance of the air is equal to the weight of the body.

Chronophotography would be a quick and easy method of measuring the resistance offered by the air to bodies of various forms, and moving with various degrees of velocity; but experiments of this kind

would have to be performed in a closed space protected from every current of air. If during the night-time a vertical beam from an electric lantern were allowed to illuminate the under surface of various-shaped bodies as they fell through such a space, chronophotographic images representing the various stages of the fall could be taken on a plate at successive intervals of time.*

But in the open air the least breath of wind disturbs the progress of the moving body, and if the fall is only a short one the resistance of the air has not time to make the velocity uniform, and more especially is this the case if the object is a very light one. In the experiment referred to on page 53, an indiarubber ball of 30 grammes weight and 11 centimetres in diameter was the object which was allowed to fall. After a descent of two metres the diminution in acceleration hardly manifested itself. But this diminution would have been very obvious in the case of a small and light air-ball.

* The Machinery Hall at the Paris Exhibition of 1889 would have lent itself admirably to experiments of this kind. The objects might have been allowed to fall from the dome of this immense building into a beam of light, and side by side with this beam a chain of incandescent lamps would have done excellently as a scale of distance; and, further, a chronometric dial with a bright needle might have served to register the time. Experiments carried out in this manner would have been very interesting from the point of view of aerial locomotion—they would have controlled and amplified the beautiful researches which are now being conducted by our colleague and friend Cailletet and by M. Colardeau at the Eiffel Tower. One could calculate the resistance of the air for any particular velocity by allowing an object to fall until, as shown on the photographic plate, the fall became uniform, because then the resistance of the air would equal the weight of the falling object.

Now, in a series of experiments, by letting the same object fall through the air, weighted with ever-increasing ballast, so that the weight increased as the following progression—1, 2, 3, etc., it could be seen at what velocity the fall became uniform. Since the resistance of the air is always equal to the weight, one could thus calculate for an object of any particular shape the law of aerial resistance for different degrees of velocity.

Ballistic Experiments.—Chronophotography can record the path taken by projectiles which travel slowly, and can show that the behaviour of such bodies is in

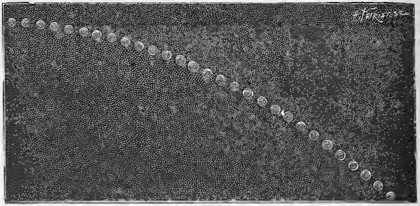

FIG. 55.—The successive positions of a projectile in respect to two axes, one vertical, the other horizontal.

accordance with the shape and the character of the propelling force. When a round projectile is thrown in a horizontal direction, the course taken is obviously parabolic; it is, however, affected by the resistance of the air, as will soon be shown. If the projectile de-

FIG. 56.—Stick thrown horizontally with a rotatory movement in a vertical plane.

parts from the circular form; if, for instance, it is a stick which is thrown in a vertical plane with a rotatory motion, the images of the stick will be found to lie in all directions, but the centre of gravity, *i.e.* the middle of the stick, will follow a parabolic course (Fig. 56).

In order that the phenomenon may appear more striking, let us unite two bodies of unequal mass by a string and throw them, giving them a twist at the same time. These two bodies (Fig. 57) will rotate round each other like a star and its satellite, but neither one nor the other will follow a parabolic trajectory; but

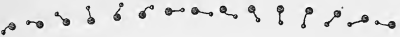

FIG. 57.—Movement of a system of two balls bound together by a string.

the centre of gravity of the system, which they together constitute, will move exactly in that path.

Now, in experiments of this kind, one can show how the resistance of the air modifies the movement of the object. Let us examine, for instance, the trajectory of a round projectile, which is thrown in a horizontal direction. Let us construct a diagram of this move-

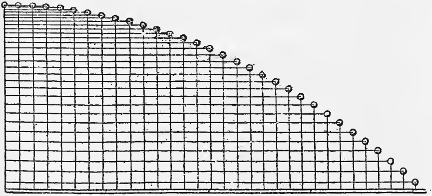

FIG. 58.—Trajectory of a projectile in respect to two axes (negative image).

ment (Fig. 58), and let us find the relationship which each position of the object bears to two axes at right angles to one another. If the resistance of the air does not interfere with the horizontal movement forward the latter should be uniformly maintained. Now, if the last section in the horizontal direction be measured

with compasses, and compared with the earlier ones, an appreciable remission in velocity will be noticed. In the same way, if the rate of fall be measured, its degree of acceleration will be found to have diminished under the influences of aerial resistance. We have even noticed in another experiment that if an object is allowed to fall vertically and then thrown in a horizontal direction from the same altitude, the duration of the vertical fall is not the same in the two cases. But in the second the resistance of the air has a greater retarding effect.

This experimental result struck Captain Uchard, who was present at the Physiological Station when the experiment was tried. Applying this knowledge, which he believed to be new, to the question of the motion of artillery projectiles, he found by calculation that the resistance offered by the air to their descent was quite different, according as they were simply let fall in a vertical direction, or were provided with an initial velocity.*

Resistance of the Air to Surfaces variously inclined.— The constant attempts that have been made to construct flying machines prove that a complete knowledge of the action of the air on inclined planes, travelling at different velocities, and at various angles, is essential for success. Clever experimentalists have succeeded in constructing small, light machines which, when let go in the air, glide about, something after the manner of a soaring bird. The eye can hardly follow the evolutions, as they are complicated, sinuous, and combined with an ever-changing inclination of the axis of the system. A sheet of Bristol board folded lengthways so as to form an obtuse angle, elevated at the back and pointed in front, was weighted by means of a

* A. Uchard, *Remarks on the Laws of Resistance of the Air*. Paris, Berger-Levrault. 1892.

steel needle run through the longitudinal fold. This little flying apparatus was allowed to fall in a vertical direction, and its chronophotographic trajectory taken by a series of exposures at intervals of $\frac{1}{20}$ of a second. Fig. 59 shows a reverse tracing of this trajectory, and must be read from the right-hand top corner downwards and towards the left.

This object falls at first vertically, with an accelerated velocity; but it is soon influenced by the rudder-like action of the curved portion behind, and swinging round advances in a horizontal direction, then by degrees it assumes an upward tendency. At

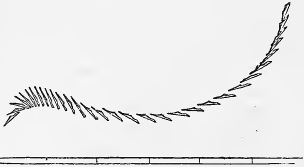

FIG. 59.—Chronophotographic trajectory of a flying apparatus describing a sinuous curve in the air (20 images to the second).

this moment the speed decreases, its axis rights itself, and becomes set in almost a vertical position. Next the axis approaches to a horizontal direction, the card takes a new plunge with the apex directed downwards, and is about to turn upside down in a new phase of accelerated velocity, only at this moment the experiment comes to a sudden termination.

All these extraordinary evolutions, which nowadays are perfectly familiar to "aviators," after long and patient researches, are explained by them as following the laws of Avanzini and Joëssel, who showed that if a thin lamina of any substance were obliquely propelled

in a fluid, the conditions of its equilibrium were modified in accordance with the velocity of movement, and in accordance with the angle formed between the axis of the lamina and the direction of movement. We cannot now dwell upon the interpretation of these experiments, which ought to be studied in a methodical manner.* It is only necessary to indicate how chronophotography may assist in researches of this kind.

Applications of Chronophotography to Hydrodynamics. —The study of the movements of fluids is very difficult, and can only be accomplished by resorting to particular methods. Thus Savart illuminated a fluid vein by an electric spark, and observed the changes in shape of the drops of fluid, as well as the distances traversed by them.

Mr. Boys, applying instantaneous photography to this study, obtained excellent results, in which the appearance of the fluid vein was reproduced by means of very short flashes of the electric light. In a moving mass of liquid, extremely complex phenomena occur; changes of surface shape, and intrinsic molecular displacements. The phenomena can be represented in the form of chronophotographs.

Let us consider the conditions represented in Fig. 50, where the water is contained in a tank with glass sides, and is illuminated from below by sunlight reflected by a mirror situated beneath the tank, and on a level with the ground. If the water is perfectly clear, the sunlight is transmitted through it without any escape in the direction of the photographic apparatus, except from that part of the surface which wets the side of the glass near the observer. In this situation capillary attraction causes the formation of a concave meniscus which extends all along the side of the glass. The light which traverses the water suffers total reflection

* See *The Flight of Birds*, chap. xix. Paris, G. Masson. 1890.

from the under surface of the meniscus. On the ground glass of the camera a very brilliant and fine line may be seen marking the level of the water, and which, moving with it, will imprint all the undulations of the water on the photographic negative.

Any internal displacement of the water can be made visible by suspending small and brilliant objects in the water, and illuminating them by the sun's rays. For this purpose pieces of wax and resin are mixed in the required proportion, the former being less dense than water, and the latter of greater specific gravity. From this solid material a number of small balls are moulded, and then silvered over, in the same way that pills are silvered by the chemist. These bright balls should be slightly heavier than water, so that when they are dropped in it they slowly sink to the bottom. If a small quantity of salt water be afterwards added, the balls gradually rise up and remain in unstable equilibrium. A paper scale, divided into centimetres, may then be gummed on to the side of the tank above the level of the fluid. This scale, which will appear in the photographs, will do very well to measure the extent of the movements which are being photographed. With such an arrangement a large number of experiments with liquids can be carried out. A few of them are here represented in the form of photographs.

Changes in Shape of Fluid Waves.—The bright line which marks the level of the fluid shows, on shaking, variations in contour such as those afforded by vibrating strings. The ventral segments and nodes sometimes occupy fixed positions on the surface of the water, as occurs in the case of a choppy sea. Sometimes they advance with varying velocity, as in rolling breakers. A similar chopping motion can be set up in the water by plunging a solid cylinder into the tank at regular intervals, and thus imparting

regular oscillations to the water. These rhythmic movements should be in that part of the tank which is furthest removed from the point of observation. The lens of the camera should be left permanently open, so that the bright line may leave a track corresponding to all the positions assumed, but with greatest intensity where the velocity is least, that is to say, in the immediate neighbourhood of the dead points which correspond to the crests and troughs, for here, just before changing its direction, the movement is at a minimum.

If one wishes to have a better appreciation of the changes in velocity during the different phases of a simple oscillation as represented by the contour of a wave, recourse must be had to chronophotography. In other words, the admission of light must be very brief, and the intervals of time perfectly regular. The successive positions of the level of the fluid will thus be obtained. These positions will be represented as curves, which will be further apart at the centre of the oscillations and closer together in the neighbourhood of the crests and troughs. If the rhythm of the movement is changed by gradual acceleration, another variety of "chopping" commences, in which the waves are shorter. In each case the profile of the wave, as it passes along in crests and troughs, takes the form of "trochoids," a name invented by those interested in hydraulics. Waves moving onward, billows, and breakers, can be taken by chronophotography, so as to show the speed at which they travel, as well as the changes in size and shape which occur in them.

We took a photograph of a wave by disturbing the water in the tank in the following way:—The cylinder described above was immersed in the water just to the right of the transparent part of the tank

in such a way that the cylinder itself did not appear in the photograph. The cylinder was lifted out and somewhat sharply plunged again into the liquid, and meanwhile a series of photographs was taken, representing the phenomenon at the commencement of the operation. At first there was a progressive series of

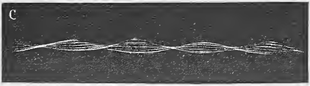

Fig. 60.—Chopping waves of very short period.

depressions visible along the surface of the water, corresponding to the moment at which the cylinder was lifted up, and then a marked upheaval at the moment the cylinder was again plunged into the water. This upheaval travelled along with diminishing amplitude, more or less interrupted by smaller

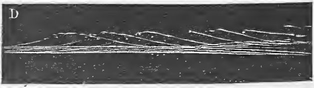

Fig. 61.—Advancing wave.

secondary waves, which advanced with the primary one. The velocity of the wave could be estimated by measuring with a scale the distance travelled by the summit of the wave during the period of one-tenth of a second, which represented the duration of the interval between each successive exposure. Progressive waves showed incomplete contours when the chronophotographic method was adopted, and that was because the hinder surface of the wave was the

best marked, and sometimes indeed the only portion visible.*

Intrinsic Movements of Fluid Waves.—A number of the bright beads previously spoken of should be thrown into the tank and the water disturbed, so as to create either waves or a chopping condition. The trajectory of these beads in different parts of the

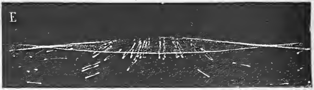

FIG. 62.—Molecular movements within a simple chopping wave.

waves can then be seen in the photographs, and consequently the intrinsic or molecular movements which occur in the same situations. In Fig. 62 is represented the appearance of a simple chopping wave as viewed from the side. Within this wave the molecules are seen oscillating, vertically in the ventral segments, horizontally at the nodes, and obliquely in the

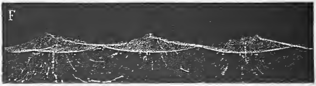

FIG. 63.—Molecular movements within a series of chopping waves of short period.

intermediate positions. To follow the phases of this movement with greater facility the waves should possess a very short period, for there the molecules may be seen describing curves, the centres of which are at the nodal points. These facts confirm the analytical studies of my colleague Boussinesq.

* It seems that, owing to the advance of the wave, the meniscus disappears from the advancing surface of the wave, that is to say, from the anterior side.

In the case of waves which travel in an onward direction, billows, and breakers, the molecular movement is different. For instance, in one photograph, taken after the sudden immersion of the cylinder, the surface molecules are seen to describe parabolic arcs in planes parallel to the direction taken by the waves. The deeper they are in the fluid the less definite are the curves described, and sometimes the direction of the movement is almost in a straight line. When the cylinder is moved with a to-and-fro movement, the molecules describe curves on the surface of the fluid which are complete rings. In all such experiments, the nature of the impulse imparted to the water so modifies the character of the movement that in order to obtain exact results the force must be applied by mechanical means instead of by the hand.

Currents and Eddies.—Owing to the circular form of the tank, it is possible to set up a continuous flow by means of a small screw immersed in the water. The latter, however, must be placed out of sight of the observer. The little bright beads will participate in every movement set up in the water.

The chronophotographs will, at any given moment, show the successive positions of these shining bodies, which will thus serve as indices of the path taken and of the velocity acquired by the various currents set up.

An obstacle, consisting of a sheet of glass, was placed in the current, making an angle of about 45° with the axis of the stream. The glass was so arranged that it touched the walls of the tank, and only presented its edge to the chronophotographic objective. A photograph was taken during a period of three seconds, and the number of images taken was forty-two to the second.

On examining this photograph (Fig. 64) it was

discovered that the various currents reached the obstacle in a more or less oblique direction, and that near the lower edge of the inclined plane the currents divided in conformity with Avanzini's theory. At the back of the obstacle the behaviour of the currents was variable. The velocity of the molecules in the different

FIG. 64.—Changes in velocity and in direction which occur in the liquid molecules of a current which meets an inclined plane.

parts of the basin must be deduced from the distance which separates any two consecutive images.

The latter are sometimes fused together in the form of a continuous trajectory, and thus demonstrate the sluggishness of the current. On the other hand, when widely separated, the intervening distances can be measured with a scale. Each interval represents $\frac{1}{42}$ of a second in time, and hence the absolute velocity

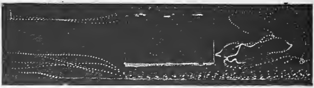

FIG. 65.—Effects produced on a current by the immersion of a solid rectangular box.

of the stream can be calculated. It is equally easy to determine the behaviour of the currents when they meet obstacles of different shape. For instance, if a rectangular box is placed in the stream (Fig. 65), of the same width as the tank, and provided with a glass top and bottom, the currents which meet it become deflected from their course, and pass with increasing rapidity

above and below. Behind the obstacle they form a number of eddies. We have also investigated the effect of a current of water coming in contact with a body of pisciform shape, that is to say, a solid body, the section of which tapers off unequally at the two extremities.*

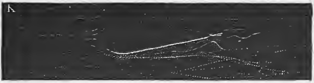

FIG. 66.—A current meeting a pisciform body at its thick end.

Experiments of this kind demonstrate in the case of fish the mechanism of swimming. They might also be useful for ascertaining experimentally the shapes which offer least resistance, either in the case of bodies immersed in flowing water or of those moving in still

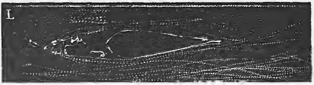

FIG. 67.—A current meeting a pisciform body at its small end.

water. The conditions, according to most authorities, are reversible.

The extent to which eddies occur, or, in other words, the loss of energy, may be regarded as a measure of the resistance offered to bodies immersed in a current.

* In order that the light might pass up through such a body, the sides were made of ebony, and the superior and inferior surfaces of celluloid—the contour of a fish being preserved throughout. The light which passed through the layers of celluloid was sufficient to illuminate the bright beads which happened to pass above the obstacle, and consequently their images appeared in the chronophotographic negatives, and showed the paths taken by the various eddies.

Now, it can be seen that if a fish-shaped body presents its thick end to the moving water the currents track along the sides, thus minimizing the deviation of the stream (Fig. 66); but if the direction of the current is reversed, so that the water comes in contact with the pointed end, the water having passed the midship-frame, falls into strong eddies (Fig. 67). This experiment confirms the opinion already held, that a "pisciform" shape is the most favourable one that a fish could possess, since the water offers very little

FIG. 68.—Fluid wave surmounting an obstacle.

resistance to such forms as have the pointed end at the posterior extremity.*

When a stream rushes violently against an opposing obstacle situated near the surface, the water rises up in a heap, and falls down on the other side in a cascade. This transient phenomenon, the details of which are not visible to the eye, can be registered in all its phases by chronophotography, and in a photograph the successive phases of the heaping up of the water, as it comes in contact with the obstacle, are shown by the variations in the water-level, while the bright beads serve as an index of the molecular movements in the depth of the basin. This brief enumeration of the applications of chronophotography for the analysis of

* Chronophotography might, it appears to us, be applied to the study of movements in air when one wanted to find the resistance offered by a body of particular shape to a current of greater or less velocity. For this purpose a number of light and luminous objects would have to be set floating in the air.

moving fluids will suffice to demonstrate the resources of the method.*

Oscillations and Vibrations.— When a pendulum swings, the suspended mass is acted upon by gravity alternately in two directions, so that the mass alternately presents positive and negative phases of acceleration, dependent, as is nowadays well known, on the continuous action of gravity. This is true also of

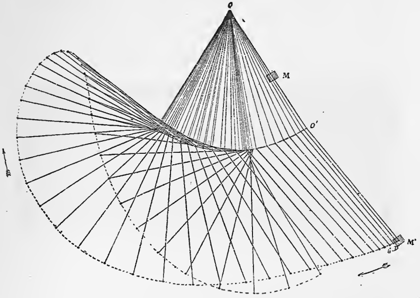

FIG. 69.—Jointed pendulum: an oscillation from right to left following on a half oscillation from left to right.

those vibratory movements in which the elastic force of a vibrating rod takes the place of gravity in an oscillating pendulum; but in some cases the conditions of movement are so complicated that it is difficult to foretell exactly what the oscillations will be. This

* Hydraulic engineers might also perhaps have recourse to chronophotography when they want to prove certain points in their theories concerning waves and currents, and even when working out the effect of different kinds of propellers. This they might do by observing the movement transmitted to the molecules of the fluid by the propellers.

happens in the case of jointed pendulums. The alternating swing of our lower extremities in running and walking is also of this nature, for while the thigh swings from the hip joint, the leg swings from the knees, and the foot from the ankle. The movements which act and react upon one another produce very complicated results. Fig. 69 shows how chronophotography can reproduce all the details.

The Vibration of Flexible Rods.—A distinguished officer in the French army occupied in studying problems in ballistics, was anxious to discover whether the transverse vibrations of the barrel of a gun were

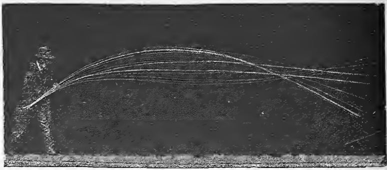

FIG. 70.—Vibrations of an elastic and wooden rod.

transmitted to the extremity of the weapon. He was under the impression that, in vibrations of this kind occurring in flexible rods, they were equally felt along the entire length, and that even in the last segments the vibrations still occurred in the form of curves. The experiment, made by means of chronophotography, showed that this was not the case. Transverse vibrations imparted to a rod were represented at the terminal segments as rectilinear discursions (Fig. 70).

The Rolling of Ships.—The so-called "rolling" of ships presents a very complicated series of problems, involving, as it does, not only the oscillations of the boat itself, but also the movements imparted to it by

the waves of a rough sea. If the characteristic movements of a boat in still water can be approximately calculated beforehand, those on a rough sea can only be ascertained by actual trial. Chronophotography readily lends itself to researches of this kind.

Experiments with floating objects, shaped more or less like boats, show that it is easy to discover the centre or the temporary centres of the rolling. By placing a little model boat in front of a dark background, and by attaching bright objects to the mast, a series of dotted lines is obtained by means of chronophotography, each of which represents one of the successive phases of rolling, and indicates the position of the mast; but if these dots are joined up so as to form continuous lines, and the latter are then produced until they intersect below the level of the water, the exact centre of oscillation can be determined for any particular moment, provided, of course, that the points of intersection are accurately obtained. If the floating object be cylindrical in shape, the oscillation takes place round the axis of the cylinder, but in other forms, especially if the object is provided with a keel, the oscillation takes place round centres which are constantly changing.

A celebrated French marine engineer assisted us in making some researches on the rolling of ships under more practical conditions; the experiments were carried out with small models which represented the commoner types of ship.

Similar researches may be carried out at the seaside by fixing electric lights to the mast-heads of boats, and by taking photographs of them during the darkness of night.

Vibrations of Metal Bridges.—M. Deslandres * has

* Deslandres, "Action of Rhythmic Shocks upon Metal Bridges," *Annales des Ponts et Chaussées*, Dec., 1892.

just made some interesting experiments on the resistance of metal bridges, by means of stylography and chronophotography. He recorded vibrations which proved that the metal arches of bridges were subject to periodic strains. The diagrams showed that, if the steps of a horse harnessed to a carriage harmonized in rhythm with the natural vibrations of the corresponding arches, the vibrations of the latter continued to increase in amplitude, until the oscillation of the bridge became thirteen times as great as when the carriage simply remained at rest on the bridge. We regret that we can do no more than simply mention this remarkable fact.

We cannot here extend the applications of chronophotography beyond the study of mechanical phenomena. The reader will doubtless realize for himself, from the instances already quoted, that such applications are extremely numerous.

CHAPTER VII

CHRONOPHOTOGRAPHY ON MOVING PLATES

Principles and History of the Method

Summary.—Janssen's astronomical revolver—Muybridge's experiments: luminous background—Photographic cameras arranged in series—Control of the instantaneous shutter by electrical means—Photographic gun—Internal structure of the instrument—Method of changing the photographic plates—Principles of chronophotography on moving plates—Employment of chronophotography—Necessity for arresting the progress of the film at the moment of exposure—Moment to choose for taking the photograph—Form and dimensions of the photographs—Regulation of the number and dimensions of the photographs—Reproduction, enlargement, and reduction of chronophotographs.

Since the invention of photography it has served as a means of comparing the present with the past by the help of authentic reproductions.

In a series of portraits taken at different periods of life, anybody can see the changes wrought by time upon the features of any particular face; an engineer can survey from afar the progress in the work of constructing a building, and a farmer the cultivation of his land.

Mr. Janssen was the first who, for the purposes of science, thought of taking by automatic means a series of photographic images to represent the successive phases of a phenomenon. The honour is due to him of having inaugurated what is nowadays called chronophotography on a moving plate.

It was proposed to take a series of photographs of

the planet Venus as it passed across the sun's disc, and for this purpose our learned colleague constructed his astronomical revolver. This instrument contained a circular sensitized plate, which at stated intervals rotated through a small angle, and at each turn

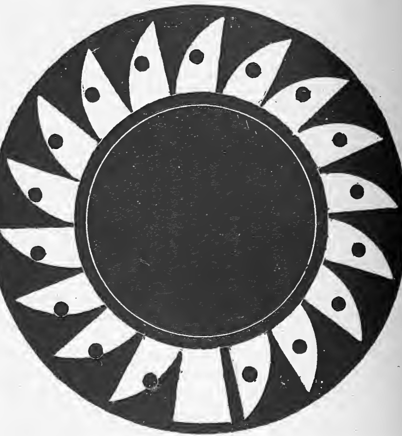

Fig. 71.—Facsimile of the print of a photographic plate obtained with the astronomical revolver of the transit of the planet Venus across the snn, Dec. 8, 1874 (by M. Janssen).

received a new impression on a fresh portion of the plate.

The photograph (Fig. 71) which was obtained by this means consisted of a series of images arranged in a circular fashion; each image represented a new position

of the planet during the period of transit, and each was separated from its neighbour by an interval of seventy seconds. In this photograph the dark silhouette of the planet stood out in strong contrast against the white background formed by the sun's surface. In the first of the series the disc representing the planet projected beyond the solar limbus, but in the third coincided with it. Mr. Janssen made the further suggestion of applying a photographic series to the study of animal locomotion.*

It remained for Mr. Muybridge, of San Francisco, to discover, by means of a rather different method to that of Janssen, the analysis of equine locomotion, as well as that of man and various animals.

Muybridge's Method and Apparatus.—Mr. Stanford, formerly Governor of California, believed that the various positions of a horse in executing its different paces could be reproduced by means of photography,

* This is how our colleague expressed himself in 1878:—"The characteristic of the revolver is that it affords an automatic means of taking a series of photographs of the most variable and rapid phenomena in a sequence as rapid as may be desired, and thus opens up for investigation some of the most interesting problems in the physiology and mechanics of walking, flying, and various other animal movements.

"A series of photographs of any particular movement, comprising the entire cycle of events, would be a most valuable means of elucidating the mechanism involved. In view of our present ignorance on the subject, one could imagine the interest of possessing a series of photographs representing the successive positions of a bird's wing during the act of flight. The principal difficulty would arise from the sluggishness of our photographic plates, for images of this kind require the very shortest exposure. But, doubtless, science will overcome difficulties of this kind.

"From another point of view, the revolver may be said to present the reverse picture to that of the phenakistoscope. M. Plateau's phenakistoscope is designed for the purpose of reproducing the effect of a movement, or of an action, by means of a series of views, which represent the component phases of the movement or action. The photographic revolver gives, on the contrary, an analytical reproduction of the movement by representing in series its elementary phases."—*Bulletin de la Société Française de Photographie*, Dec., 1876.

and determined to have experiments made on the subject. He was fortunate enough to secure the services of Mr. Muybridge, who obtained immense success in photographing different kinds of paces. A description has been given of these experiments in a work published under the auspices of Mr. Stanford, by Dr. Wellmann.*

The scene of the operations was a track which

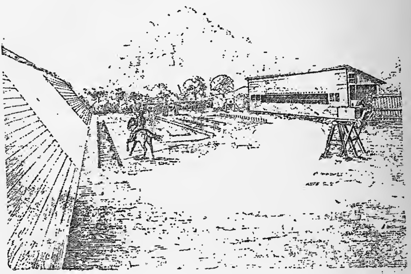

FIG. 72.—Field of operations arranged by Mr. Muybridge. On the left there is an inclined screen which reflects the sun's rays, and before which the horse passes. On the right there is a series of photographic cameras. Some other cameras mounted on trestles enable the operator to obtain simultaneous photographs of a horse from various points of view.

passed in front of a white inclined screen, and so situated that it reflected the sunlight in the direction of the photographic apparatus (Fig. 72). The screen was marked with divisions at equal distances, which, when reproduced in the photograph, served as a means of measuring the distance traversed by the horse.

A series of cameras was drawn up opposite to this

* *The Horse in Motion, as shown by Instantaneous Photography.* London, Turner & Co., 1882.

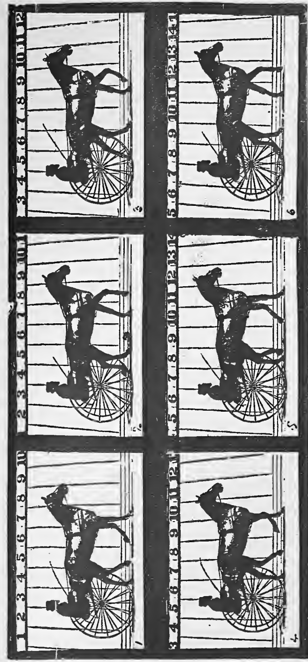

FIG. 73.—Six successive photographs of a horse at a walking pace; the first of the series is above and to the left. The rate of *going*, according to Muybridge, is 106 metres per minute.

The interval which separates each of the divisions on the screen is 0·58m. The marks serve to determine the rapidity of movement and to measure the extent of the limb movements.

track, and electric wires were stretched across the path at intervals. These latter communicated with electro-magnets, each of which held the shutter of one of the cameras tightly closed. The horse, in following the track, broke these wires one after the other, and brought about the instantaneous opening of the corresponding shutter, each exposure allowed a photograph of the animal, in one or other of its positions, to appear on the plate.

These valuable experiments settled certain points with regard to the paces of a horse in motion, about which there had been, even among specialists, great divergence of opinion. Muybridge's figures demonstrate the successive movements of the horse's limbs, as well as the corresponding position of its body. The extent of the movement can be measured by means of the divisions marked on the screen (Fig. 73).

In an album kindly presented to us by Mr. Muybridge, one can see how all kinds of equine paces are represented, as well as those of the bull, the stag, the dog, and the pig. Instantaneous silhouettes of men running, jumping, and wrestling, present certain attitudes which are very interesting from the point of view of artistic reproduction of such movements.*

The Photographic Gun.—After the introduction of instantaneous photography, it seemed to us that the movements of a flying bird could be analyzed by this method. We therefore asked Mr. Muybridge to make use of his apparatus to study the flight of birds. He hastened to accede to this request, and when he came

* In Mr. Muybridge's first work he only used the old-fashioned wet-plate system. The discovery of the dry gelatine plate, sensitized with bromide of silver, allowed him latterly to pursue his studies under more favourable conditions, and to publish magnificent plates of animals in motion.

During late years, M. Ottomar Anschütz (of Lissa) has obtained, by Muybridge's method, a very beautiful series of photographs showing men and animals in motion.

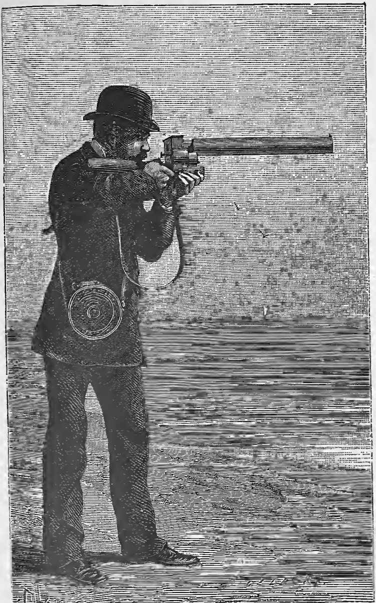

FIG. 74.—The photographic gun.

to Paris, in August of 1881, he brought us several prints of pigeons photographed in $\frac{1}{500}$ part of a second. Each of these photographs represented a number of flying pigeons in different positions, one with its wings raised, another with them in front, and another with them depressed. These positions appeared to us to coincide almost exactly with those which we had predicted from studying the mechanism of flight by the graphic method.*

But beyond the fact that these photographs were not sufficiently clear, they failed in that which gave so much interest to those of the horse in motion, namely, the arrangement in a series which showed the successive attitudes and positions. This is because it is impossible to apply, in the case of a bird in free flight, the method which succeeded so well in the case of a horse, and which depended on the animal itself opening a series of photographic shutters.

We determined to invent an apparatus based on the same principles as that of M. Janssen, but capable of giving a series of photographs at very short intervals of time,—$\frac{1}{12}$ of a second instead of the 70 seconds which separated the photographs of the astronomical revolver —so as to procure the successive phases of the movements of the wings. This instrument, gun-like in form (Fig. 74), made it possible to follow the flight of a bird by aiming at the object in the ordinary manner. The moment the trigger was pulled the sensitized plate received an impression, then moved on only to receive another, and so on, but always stopping each time that the opening of the shutter allowed the light to fall on the plate.†

* "The Graphic Method," p. 211.

† The following are the details of the construction. The barrel of the gun is a large blackened tube (Fig. 75), which contains an ordinary photographic lens. At the hindermost part, mounted firmly

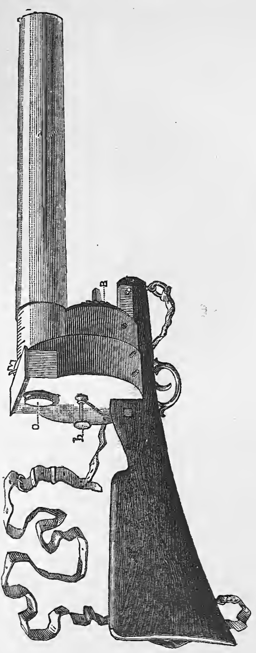

Fig. 75.—External appearance of the photographic gun.

The gelatine plates, sensitized with bromide of silver,

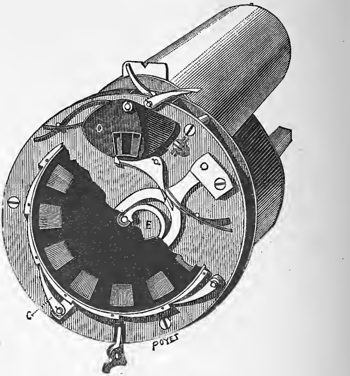

FIG. 76.—Details of the interior of the photographic gun.

on which the photographs were taken, were cut with a diamond to a circular or octagonal shape, as is shown

at the butt end, is a large cylindrical breech which contains the clock-work mechanism. The axis of the breech is seen projecting at B. When the trigger is pulled the wheels begin to rotate and transmit the necessary movement to the different parts of the instrument. A central axis, which revolves 12 times in a second, controls the movement of all the individual parts of the apparatus. In the first place (Fig. 76), there is an opaque metal disc provided with one small opening. This disc constitutes the shutter, and only allows the light, which passes through the objective, to gain an entrance 12 times in a second, and then only for a period of $\frac{1}{720}$ part of a second. Behind the first disc there is another provided with 12 openings which rotates freely on the same axis as the first, and behind these, again, there is room for the sensitized plate, which may be circular or octagonal in shape. This fenestrated disc should rotate intermittently so as to come to rest 12 times in the second just opposite the beam of light which penetrates the instrument.

in Fig. 78. In this photograph the successive positions of a flying gull are shown at intervals of $\frac{1}{12}$

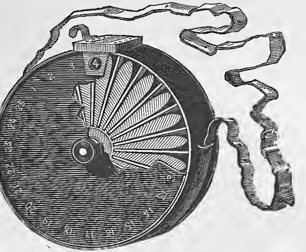

FIG. 77.—Special box for holding the photographic plates.

of a second. These little images, when enlarged by projection, furnish curious details with respect to the position of the wings, and the torsion of the remiges

An eccentric, E, placed on the central axis, produces this intermittent rotation, by transmitting a regular to-and-fro movement to a rod which is furnished with a catch, C. At each oscillation this catch is held by one of the teeth which form a sort of circlet round the fenestrated disc.

A special shutter, O, effectually prevents the light from penetrating into the instrument as soon as all twelve photographs have been taken. There are other arrangements for preventing the sensitized plate from passing, by reason of its acquired velocity, the position assigned to it by the catch, and where it should remain perfectly still during the period of illumination.

A pressure button, b, Fig. 75, is brought into close contact with the plate, as soon as the latter is introduced into the gun. Under the influence of this pressure the sensitized plate sticks firmly to the posterior surface of the fenestrated disc, which is covered with india-rubber to prevent it slipping.

The object is brought into focus by elongating or shortening the barrel, and thus removing or approximating the lens, and finally the process is corrected by looking with a microscope through an opening, O, made in the breech of the gun, and observing the definition on the ground glass.

by the resistance of the air, as is shown in Fig. 79; but in the majority of cases the images are too small to stand enlargement.

To obtain larger images, certain authors, among others, M. Londe and General Sébert, have constructed an apparatus furnished with multiple objectives, the shutters of which open in succession. But such a

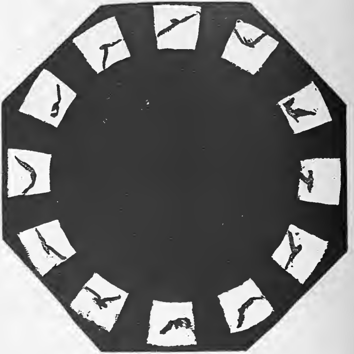

FIG. 78.—Photograph of a gull during flight. Reproduction by means of *Heliogravure* of a *cliché* obtained by means of the photographic gun.

multiplication of objectives is productive of serious difficulties. Besides making the instrument very costly, especially if objectives of good quality are used, photographs are produced which, taken from different points of view, are incapable of comparison. This is not the case with photographs of small dimensions taken at a short distance. These cameras

regard, if one can use the expression, the object from different points of view. Now, these variations in perspective, although presenting few difficulties when operating from afar on objects of large size, would make the study of small objects at close quarters a matter of great difficulty,* still less would they permit one to photograph objects of microscopical size. For this reason we determined to employ a single objective.

In order that we might simplify the instrument as much as possible, we united in a single apparatus all the accessories necessary for chronophotography on fixed or moving plates, as well as for regulating at will the frequency and duration of the exposures.

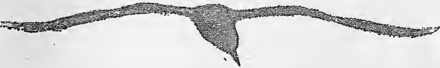

FIG. 79.—Enlargement of one of the photographs obtained with the photographic gun.

Principles of Chronophotography on Moving Plates.— The weak point of the photographic gun was principally that the images were taken on a glass plate, the weight of which was exceedingly great. The inertia of such a mass, which continually had to be set in motion and brought to rest, necessarily limited the number of images. The maximum was 12 in the second, and these had to be very small, or else they would have required a disc of larger surface, and consequently of too large a mass.

These difficulties may be overcome by substituting for the glass disc, a continuous film very slightly coated with gelatine and bromide of silver. This film can be made to pass automatically with a rectilinear movement across the focus of the lens, come to rest at each

* See Chap. v. p. 81.

period of exposure, and again advance with a jerk. A series of photographs of fair size can be taken in this way.

The size we chose was 9 centimetres square, exactly the right size to fit the enlarging camera, and by which they could be magnified to convenient proportions. Now, as the continuous film might be several metres in length, the number of photographs that could be taken was practically unlimited.

Arrangement of the Chronophotographic Apparatus.—

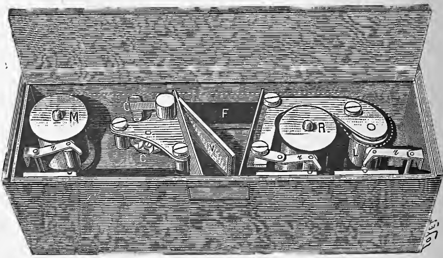

FIG. 80.—Internal structure of the photographic chamber.

The necessary elements for taking successive images on a continuous film are united, as we have said, in the apparatus already known to the reader. The back part of this apparatus has a special compartment, the photographic chamber (Fig. 80), in which the sensitized film is carried. To admit light, all that is necessary is to substitute for the frame which carries the fixed plate another frame provided (Fig. 81) with an aperture, the size of which can be varied at pleasure. This is the admission shutter. At each illumination the light

passes through this aperture, and forms an image on the moving film, which has previously been brought into focus.

The film unrolls itself by a series of intermittent

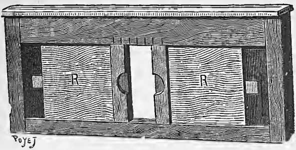

FIG. 81.—Admission shutter which is substituted for the dark slide when working with a roll of film. The size of the aperture can be regulated by the side screens R R according to the dimensions of the intended image.

movements, by means of a special mechanical arrangement, which enables it to pass from one bobbin to another. The arrangement of these bobbins must first occupy our attention, for the possibility of loading

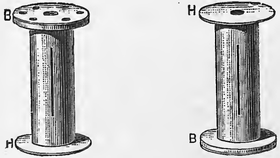

FIG. 82.—Two metal bobbins for carrying the sensitized film. The two bobbins are placed in different positions: the letters H and B indicate respectively the upper and lower parts.

or unloading in the light is dependent on their construction.

The bobbins are made of metal, and two projecting plates are fixed to the two ends of a light cylinder. The upper of these plates is thin and the lower one

thick. The bobbins rotate on a vertical pin which runs through their centre. A circle of little holes bored in the lower plate of the bobbin forms part of the motor mechanism. When a peg fixed in a revolving plate enters one of the holes of the other plate, the two will rotate together, carrying the bobbin with them.

One of these bobbins serves to store the sensitized film, which is rolled round it, and which is finished off at the ends by strips of opaque paper pointed at the extremities. One of these pointed ends fits into a slit made lengthways in the bobbin, and the rolling up can

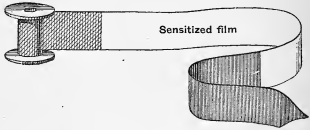

FIG. 83.—Showing how the film is lengthened at its two extremities by the opaque bands of paper.

thus be effected. In the process of rolling, the strip of paper comes first, then the sensitized film which is joined to it, and then the second strip of paper. An elastic band put round the bobbin keeps the entire roll securely fastened. This operation is executed in the dark room, but as soon as it is finished the charged bobbin can be carried into the light, for the sensitized film is protected by the coils of opaque paper.

Charging the Apparatus.—On opening the photographic chamber, two vertical pins may be seen (Fig. 80); that on the left receives the supply bobbin, the filling of which has already been described, and that on the right is for the receiving bobbin—that is to say, the one which will receive and roll up the film, or

as much of it as has been used in taking the photographs. That this may work properly, the end of the strip of paper which is last wound round the supply bobbin must be fixed in the slit of the receiving bobbin. The method of rolling is represented in Fig. 84. The two bobbins being placed on their respective pins, the strip of paper passes through a vertical slit, and through which it keeps running, pulling the sensitized film after it. Two pressure rollers (r r, Fig. 80) are applied to the surface of the bobbins to ensure regularity in rolling and unrolling.

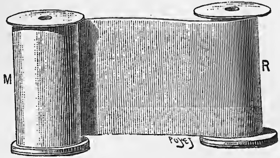

FIG. 84.—Supply bobbin ready charged. M, the end of the paper which covers it, must be unrolled and wound round the receiving bobbin, R, in an opposite direction.

We shall not describe the mechanism which produces the intermittent movement of the film. The new arrangement which we have adapted to the apparatus for making the operation more certain, and its employment more easy, differs noticeably from that which we have described before.*

It would be better for the beginner, instead of relying on a written description, to make a few experiments with a strip of ordinary paper in place of the sensitized film, and thus he would soon acquire proficiency in filling the bobbins, and passing them quickly into their proper chamber.

* *Revue Générale des Sciences*, November 15, 1891.

A crank placed behind the chronophotographic apparatus turns all the wheels of the instrument, as well as the circular diaphragms. A movement, so rapid as this must necessarily be, is bound to be continuous, for it would be impossible, as in the case of the photographic gun, to remit or continue the movement of such heavy bodies. The film itself comes to rest at the moment of exposure, arrested by a special mechanism which allows it to continue its movement as soon as the image has been taken.

Necessity for arresting the Progress of the Film at the Moment of Exposure.—Some people have thought that, by using such a complicated apparatus as that which we have employed for arresting the movement of the film, we have given ourselves unnecessary trouble, and it has been said that for very short exposures the movement of the film might be neglected. It would be easy to prove by calculation that, during the period of the exposure, say $\frac{1}{1000}$ part of a second, the film would move enough to deprive the photographs of that clearness upon which their value depends. But it is simpler and perhaps more convincing to show by an experiment that without these periods of arrest good images are not to be obtained.

By alternately suppressing and inducing an arrest of the film at the moment of exposure, we obtained a series of images which were alternately blurred and distinct. In Fig. 85 two such consecutive images are shown. The different degrees of definition is so obvious that it is useless to further insist on the necessity of arresting the film during the period of exposure.

The Moment to choose for taking the Photograph.—When the chronophotographic apparatus is pointed at the object the movements of which are to be studied, the wheels are put in motion by turning a crank,

the different parts acquire a uniform speed, but the film remains stationary until the moment when the observed phenomenon takes place. At this juncture the operator presses the trigger, the film begins to move, and the photographs are taken as long as the pressure is maintained on the trigger; as soon as the pressure is remitted the progress of the film is arrested. The employment of this trigger makes it possible to

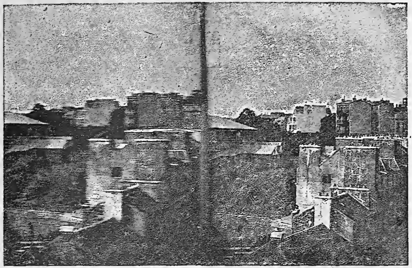

FIG. 85.—Two successive photographs taken on a sensitized film. The image on the left is taken without arresting the onward movement of the film at the moment of exposure; that on the right is taken with the film at rest.

continue taking photographs until the bobbin is exhausted.

Shape and Size of the Photographs.—The shape and size of the photographs should be in conformity with the character of the subject, so as to utilize to the best advantage the surface of the film. For this purpose the opening of the admission shutter should be regulated to meet the requirements of the case, and the position of the apparatus correspondingly altered. Thus the photograph of a man in an upright position

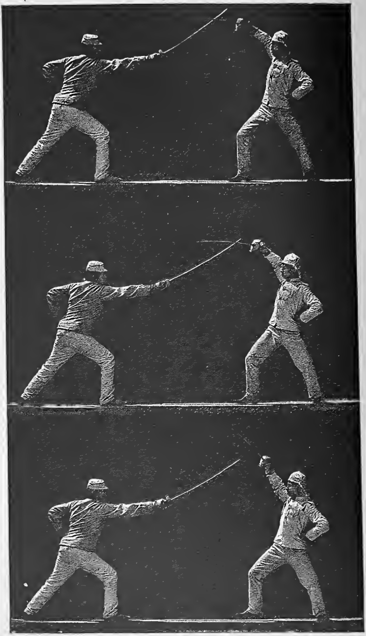

FIG. 86.—Sword-stroke. The series must be read from below upwards.

executing movements on the same spot should be taken on a surface the height of which is greater than its breadth; on the other hand, two men occupied in fencing would require an opening the breadth of which is greater than the height (Fig. 86). The same is the case in taking successive photographs of a man rowing. The background of the image should be regulated by reducing the opening of the admission shutter to a greater or less degree. When the images occupy most space in the horizontal direction the camera should be turned over on its side; the successive attitudes should then be viewed by beginning at the top and travelling downwards.

Regulation of the Number and Size of the Images.—If the progress of the film is uniform, and allows, say, ten large images to be taken in the second, twenty images half the size may, if necessary, be taken in the same time, or thirty images a third of the size, and so on. To effect this, the size of the admission shutter must first be reduced to one-half or one-third of its normal size. It is important that the circular diaphragm should permit at the same time the exposures to be twice or three times as numerous. The fenestrations in the diaphragm should, therefore, have curtains which can be drawn aside or closed as required.*

Reproduction, Enlargement, and Reduction of the Photographs.—The size which we have selected for chronophotographic images (9×9) is, as we said, precisely that adopted for the plates used for enlarging-cameras. Each photograph can be thrown on a screen, if required for public demonstration. The strip of

* In the arrangement we previously adopted, the number of times the film was brought to a position of rest had to be regulated by a very delicate manœuvre; this was dispensed with in the new arrangement.

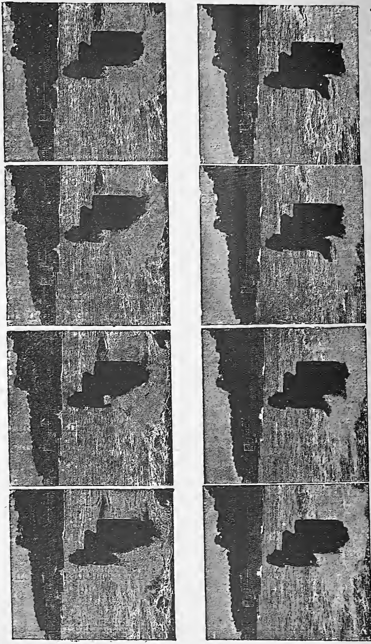

FIG. 87.—Series of photographs to show the successive phases of the movement of a wave. (Simili-gravure, the photographs being reduced to one quarter of their original size.)

film itself, or at least the series of positive images obtained from it by superposition on a similar strip, can produce a series of effects following one another in such rapid sequence that the spectator sees the movement reproduced in all its phases. This synthetical representation of movement will be described further on. For ordinary publication the images are reproduced by means of a special process called "simili-gravure." Most of the figures scattered in the text were obtained by this process. But as simili-gravure requires a special treatment of dotting, or hatching, to give the shapes of the shadows, it would be of no use for reproducing very small photographs of microscopical objects, nor for very graduated shading such as is required for the delineation of muscles. In these two cases we had recourse to impressions made with lithographer's ink. When a long series of photographs has to be reproduced, showing the successive phases of a phenomenon, plates of special size must be used, or otherwise only a small number of images can be obtained. If these photographs are reduced so as to suit the limitations of a page, they lose much of their merit and interest. This occurred in the case of Fig. 87, in which eight reduced images are represented, each occupying one-fourth of the space occupied in the original plate.

CHAPTER VIII

HUMAN MOVEMENTS

From the Point of View of Kinetics

Summary.—Some movements in man; the study of them by the graphic method—Speed of different paces in man; relationship between the frequency and length of stride—Duration of the rise and fall of the foot in walking and running—Path described by any particular part of the body during different paces; mechanical means of recording it—The study of movements in man by means of chronophotography on fixed plates; long-jumping; high-jumping—Skilled movements, fencing, etc.—Jumping from a height—The swing of the leg in walking.

Some Movements in Man.—The ancients, who positively worshipped physical exercises, only understood them from the point of view of practical experience; they were entirely ignorant of the functions of muscles, but they knew how to turn out a good runner or wrestler. Later on, as anatomy revealed the structure of the human frame and the muscular system, it was the current belief that the function of an organ was dependent on the shape or form, and in consequence a system of physical training was established on entirely erroneous theories. Doubtless it would have been wise to have retained the traditions which were founded on practical experience, until such time as Science was in a position to impose really useful amendments.

It was not till the seventeenth century that Borelli

threw some light upon the mechanism of animal locomotion.*

This learned Neapolitan professor applied to the case of moving creatures the same mechanical laws which had recently been discovered by Galileo, and showed that the effect of muscular force made itself felt partly on the mass of the body, and partly on another mass which was called the point of resistance, and he reduced to its simplest form the general theory of locomotion. But, to impart some accuracy to the study of human movements, it was found essential to construct instruments to measure the range, velocity, and sequence of the various phases of movement, not only in walking, but also in running, jumping, etc. The force exercised in executing these different movements should also have been measured; but the necessary instruments were not in existence.

Two celebrated mathematicians, the brothers Weber, realized the necessity for accurate measurements, but inefficient instruments were all they had at their disposal. A level piece of ground of known length, a watch provided with a second's hand, and a performer was all they had to work with; they could therefore only obtain a small number of measurements with regard to the relationship between the frequency and length of stride, of the extent of the vertical head displacements and of the various inclinations of the body, and even then these measurements had to be corrected.

With the assistance of the graphic method, we determined to introduce accuracy into these studies, but it was chiefly by means of chronophotography that we arrived at a scientific interpretation of the various bodily movements.

Before giving the results furnished by this method,

* Borelli, *De Motu Animalium.*

and thereby demonstrating its importance, it would be as well to briefly sum up the results of other methods. Such a review is the more necessary, because chronophotography has nothing to do with other methods, its application only becomes of real value when mechanical methods can no longer be employed.

Speed of Different Paces in Man, Relationship between the Frequency and Length of Stride.—A man in walking or running covers at each stride a certain amount of ground, and the more steps he takes in a given time the greater is the total distance he covers. Similarly, if the stride is increased, but the number kept the same, the distance will be proportionately greater. Speed, therefore, depends on two factors: the length and frequency of the stride. Now, the brothers Weber enunciated, as the result of their studies, that the length of stride became greater as the frequency increased; a slow, processional step, for instance, being shorter than one executed at a greater rate. If this were the invariable law, the march of troops might be indefinitely accelerated by quickening the time of the drums or trumpets which regulated the pace. But our experiments showed that this theory of the brothers Weber was only correct up to a certain point, namely, until the step was so quick that it amounted to a run, and after that point was reached the rate of progression soon diminished. Our experiments were made in the following manner:—

Being fully persuaded that, if one wanted to estimate exactly the average length of stride, it was necessary to carry out the experiments on a long track, we laid out at the Physiological Station a circular and perfectly horizontal course, five hundred metres in circumference; a telegraph wire ran all the way round the track, and the posts were placed at intervals of

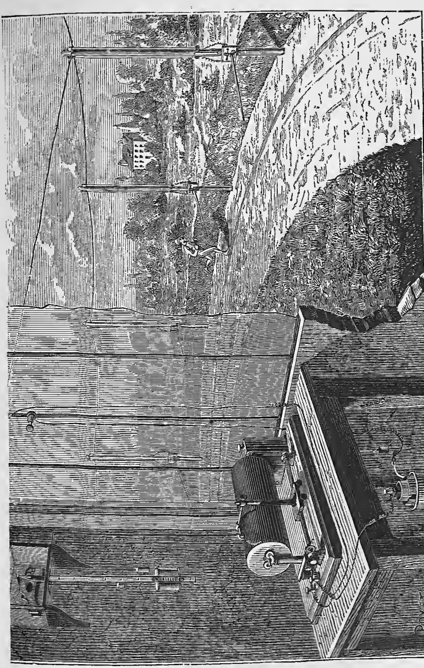

Fig. 88.— Arrangement of the odograph and of the track at the Physiological Station.

fifty metres. Each post was provided with a little contrivance for breaking the circuit the moment the performer came abreast of the post. Within the laboratory a recording apparatus—"the fixed Odograph"—was in communication with the telegraph wires.

In this apparatus a needle traced a horizontal line upon the paper which covered a revolving cylinder, and every time the performer broke the circuit, as he passed a post, the needle was displaced for a moment from its course and executed on the tracing a rectangular inflection.* As these inflections were repeated every time the performer passed a post and completed a distance of fifty metres, it followed that, at the end of a given time, the odograph had described a zigzag curve which showed the rate of progression.

Time is measured on the odographic curve by referring to the horizontal divisions, which are marked along the axis of the abscissæ, and are numbered 0–16, each division representing one minute. The distance travelled is measured in metres along the axes of the ordinates. So that for every point of the curve the time occupied and the space traversed may be estimated by referring to the intersections of the vertical and horizontal lines. The relationship of these two values gives the actual speed.†

Instead of the staircase line (*a*) traced by the odograph, it is better to draw a line connecting all the angular projections on the curve; in this way were obtained the lines *o*, *b*, *d*, - - - *i*, which express by their variation in inclination the speed of different paces. They represent a uniform rate when they are rectilinear, a variable speed when they are curved. So far we only know the rate of progression with its two factors—time occupied and space traversed—at each

* See, for details of the experiment, *La Nature*, 1887.

† See *C. R. de l'Académie*, November 3, 1884.

point of the curve. It was important from one point of view to know the number of steps taken. For this purpose we placed in the centre of the track a bell which rang at regular intervals, and with which the performer kept time. The intervals could be regulated by means of a pendulum, the length of which could be varied at pleasure. It was situated inside the laboratory, and could control the rate of ringing for anything between 40 and 120 strokes a minute. The number of steps per minute being thus known, one could substitute in the odographic tracing the total number of steps taken for the time occupied, and by

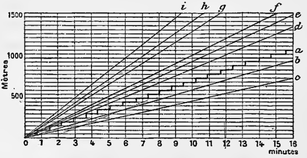

FIG. 89.—Chart of the *fixed* odograph to show paces of different velocity.

dividing the distance traversed by that number, we could arrive at the average length of stride.

It was from such data that Fig. 90 was constructed. This diagram showed that the length of stride increased as the step was quickened, that is to say, when the rate was between 40 and 75 per minute. This was just as the brothers Weber had showed; but when the rate was quickened beyond that point, the length of stride decreased, and finally at 85 steps per minute and onwards the total rate of progression began to diminish. That is to say, the shortening of the step became so pronounced that in spite of the increase in frequency, the total distance traversed in a given

time was markedly diminished. These experiments, which for the most part were carried out on marching troops, have been repeated on a large number of men of various sizes, both with and without burdens, and in the case of veterans as well as in the case of recruits.

The influence of various inclines on the length of

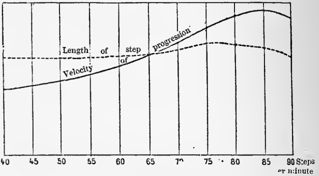

FIG. 90.—Curves to show the rate and length of the stride.

stride was also investigated,* as, too, was the shape of the shoe both with respect to the length of the sole and the height of the heel.†

All these experiments on running and walking were carried out on men, some of whom carried weights, while others were unburdened. Exact results have been

* Experiments on different kinds of tracks were made elsewhere than at the Physiological Station by a slightly different method. A track of known length, an automatic counter of the number of steps, and a watch with a second's hand furnished the necessary appliances.

† The length of a step does not entirely depend on the degree of separation of the legs; this would be the case if, as in the legs of a compass, they only touched the ground at two points; but the length of foot must be taken into consideration when estimating the length of a step, for the foot touches the ground first with the heel, while the toe is the last part to leave the ground. Thus in estimating the total length of the stride, the length of the foot which is extended along the ground must be added to it. It follows, then, that for legs of equal length, those which have the smallest feet take the shortest steps, and, similarly, that a short boot will have the same shortening effect. Finally, a high heel, by curtailing the total length of foot in contact with the ground, will also detract from the length of stride.

obtained without the help of photography; moreover, the latter method, although it could give exact details of any particular, for instance, as to the length of any stride considered by itself, could not furnish the required averages.

Mechanical Record of Movements in Walking.—We saw in Chapter I. how the duration and sequence of the rise and fall of the foot in walking could be recorded by mechanical means. This chronographic record was effected by transmitting through the medium of pneumatic tubes the pressure of the foot on the ground to the registering tambours. We showed the result of these observations, and shall now continue the investigation.

In ordinary walking on level ground one foot leaves the ground as the other reaches it. In the case of a man who carries a weight, or who walks uphill, or mounts a staircase, the foot in contact with the ground does not leave it until the other has been in contact with it for some time. There is then a period, more or less prolonged, during which both feet simultaneously rest upon the ground.*

In running, the body remains suspended in air for a brief moment between two successive contacts, and this suspension lasts longer as the speed of running increases.

Path described by any Particular Part of the Body during Different Paces.—So extensive are the movements in walking, and even more so in running, that mechanical registration of these movements becomes very difficult, and, further, they nearly always take

* By substituting electric for pneumatic signals, M. Demeny believed that he detected, even in ordinary walking, a short period during which both feet were simultaneously on the ground, and that this period was prolonged as the pedestrian became more tired. These results would be most important if, so to speak, they provided a means of measuring fatigue.

place in three directions of space, and thus require simultaneous registration by three curves.

Nevertheless, our late pupil and friend, Carlet,* obtained, by the geometrical combination of three curves recorded simultaneously, the actual path described by a selected point on the body of a man walking. A movement of this nature can only be represented by a solid figure.

Carlet used for this purpose a piece of wire twisted in different directions. A flat figure, even with the help of light and shade (Fig. 91), can only give a very imperfect representation of a movement of this kind.

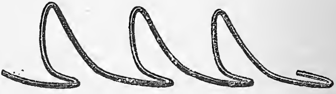

FIG. 91.—The trajectory of the pubis of a man at a walking pace. A metal wire twisted in various ways indicates the variations of this curve in respect to the three directions of space.

Stereoscopic images alone are capable of giving a satisfactory picture of it. Now, we said in Chapter II. how easily images of this kind might be obtained. Fig. 14 shows a trajectory very similar to that laboriously obtained by Carlet.

When it is a matter of registering all the details of a man's movements, both as regards change of position and attitude of the body and limbs, mechanical registration is out of the question. It is at this point that chronophotography comes to the rescue.

The Study of Movements in Man by means of Chronophotography on Fixed Plates.—In Chapter II. we showed how to obtain on fixed plates a series of images corresponding to the successive phases of a movement,

* Carlet, "Essai Expérimental sur la Locomotion de l'Homme," *Annales des Sciences Naturelles*, 1872.

and we gave as examples chronophotographic representations of walking and running. Fig. 92 shows how a long-jump is executed. The figures in the photograph reveal attitudes which the eyes are not accustomed to see; they express better than language the way in which the movement is executed, and allow the different phases to be followed with ease. In certain respects they correct ideas which existed on the subject of the mechanism of jumping. Take, for instance, the theory which led teachers of gymnastics to recommend their pupils to land on the toes in order to break the shock on coming in contact with the ground. Our figures show, on the contrary, that in long-jumping it is the heels which first reach the ground, and that it is the flexion of the legs and thighs that breaks the shock. To sum up, chronophotography affords the means of understanding the real characters of a movement, and is therefore of value in teaching athletic exercises. Guided by photographs of this sort, it is easy to imitate the style of walking or running set by the person who serves as a model, and to reproduce his method of extending or flexing the limbs, of swinging the arms, and of bringing the feet to the ground or removing them from it. It would be much more difficult to imitate these movements by merely watching the instructor, because, especially in rapid movements, the motions are so transitory as to escape observation.

In Fig. 92 the number of images is only five to the second; this, however, is sufficient to show the series of actions which must be accomplished in executing a jump of this kind. By looking at these images in the order of execution, it is seen that the jumper acquires by a preliminary run sufficient impetus to cover a considerable distance during the period of suspension.

FIG. 92 —Successive phases of a long-jump. (Chronophotography on a fixed plate.)

At the moment of jumping, the leg in contact with the ground is violently extended, thereby imparting a vertical impetus to the body, at the same moment the arms are thrown up, giving additional energy to the effort.

The successive images show the jumper after he has left the ground, with the arms elevated in front and the legs separated; later on, the arms drop, and the legs are brought nearer together as they become more advanced in front of the body, so that finally the heels of both feet touch the ground together, and in front of the centre of gravity of the body. A fall on the face is thus obviated. At the moment of descent the legs are flexed, so as to counteract the impetus of the body.

The distance cleared is more or less extensive, according as this series of actions is skilfully or clumsily executed, and according as the jumper lands advantageously on the ground or the reverse. If he has miscalculated his speed, and his feet are not sufficiently far advanced in front of him at the moment of landing, he cannot retain his balance, but has to run forward a few steps until the impetus is checked.

In the case of pole-jumping (Fig. 93), it is equally easy to follow the various stages. The jumper fixes the end of his pole in the ground, and at the same time raises himself by a vigorous extension of the legs. The combined action of the vertical and horizontal impulses imparted to the body enables it to describe an arc of a circle. In falling, the body will continue this curve, and will land just as far in advance of the point of the pole as it was behind it at starting. But a skilful jumper can avail himself of an artifice which enables him to augment his jump considerably. It consists in elongating the radius of the circle

FIG. 93.—Successive phases of a pole-jump. (Chronophotography on a fixed plate.)

described by climbing up the pole at the moment it passes the vertical, and then by inclining the body until it becomes almost horizontal, that is to say, at right angles to the radius of the circle described, the jumper falls naturally on his feet at a much greater distance from the starting-point.

In pole-jumping, the initial impetus is not, as in the case of long-jumping, the only force upon which the extent of the jump depends; but this distance can be augmented by manœuvres of the jumper, who can make use of his arms by employing the pole as a fixed point of support while he is still in the air.

For a more detailed study of movements in physical exercises, recourse must be had to those outline or geometrical photographs of which we have already given an example in the case of a man walking. A man dressed in black velvet with bright lines down his arms and legs produces Fig. 94 as the result of a long-jump preceded by a preliminary run.

Here all the phases of the movement are arranged in close series with no sudden transitions, because of the great number of images (twenty-five to the second) taken during the jump.

In order to render chronophotographs of movements more instructive, these images should be taken from very strong and competent athletes; for example, from the prize-winners at athletic sports. These champions will thus betray the secret of their success, perhaps unconsciously acquired, and which they would doubtless be incapable of defining themselves.

The same method could equally well be applied to the teaching of movements necessary for the execution of various skilled industries. It would show how the stroke of a skilful blacksmith differed from that of a novice. It would be the same in all manual performances, and in all kinds of sport.

CHRONOPHOTOGRAPHIC PRINT OF A LONG-JUMP PRECEDED BY A RUN.

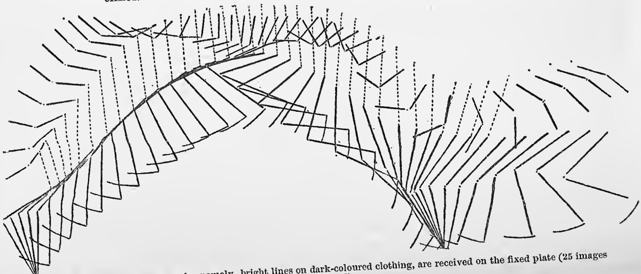

FIG. 94.—Incomplete photographs, namely, bright lines on dark-coloured clothing, are received on the fixed plate (25 images to the second).

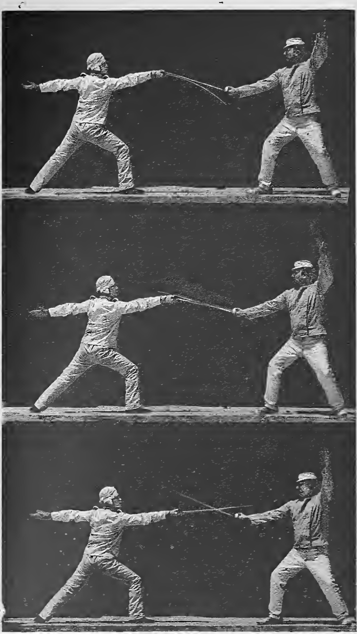

FIG. 95.—Fencing. Read from below upwards.

From a series of diagrams of the kind, we have easily been able to follow the successive actions of a man mounting a bicycle. The study of these figures would be an excellent preparation for any one wishing

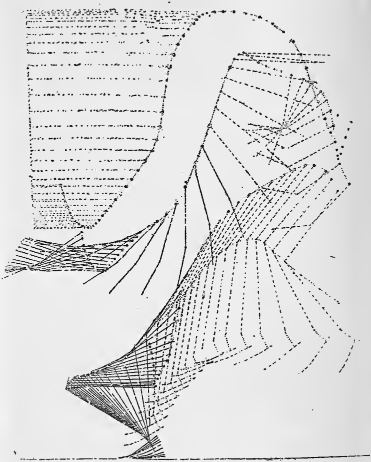

FIG. 96.—Jump from a height with flexion of the legs to break the fall.

to learn exercises of this kind. In all trials of strength, and in fencing, certain actions occur which the eye is unable to follow and language fails to express. If an attempt is made to teach them by executing them slowly, their whole character is completely changed.

Here, again, a series of photographs, taken at the rate of 10 to 20 per second, helps to explain all the details of the movement.

Unfortunately, we could not represent a whole series

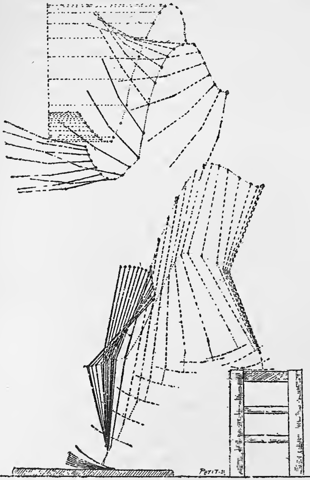

FIG. 97.—Jump from a height with stiffened legs.

of this kind in the compass of this book, and we can only give a few fragmentary examples. We have already shown in Fig. 86 three successive phases of broad-sword-exercise. Fig. 95 similarly shows three

instantaneous views of two men fencing; both sets of combatants represented belonged to the Italian school.

Geometrical photographs sometimes elucidate extremely complicated movements. Thus, in jumping from a height (Fig. 96), the position of each point of the body, in its various phases of movement, is expressed by an almost continuous curve. The axes of the long bones make the figures more or less complicated, revealing movements the existence of which would never have been suspected from mere ocular

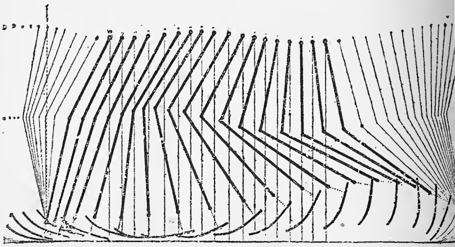

FIG. 98.—Oscillations of the leg in running. (Geometrical chronophotograph.)

observation. In jumping from a height, the difference between landing gently with no shock and landing with rigid legs is clearly seen by comparing Fig. 96 with Fig. 97. The latter corresponds to the drop with stiffened legs, namely, in which the shock is not broken by flexion of the legs.

In complicated actions, a diagram can be obtained of only one part of a movement; for instance, in running it may only be necessary to observe the phases of oscillation of the legs—this can be done by limiting

the diagram to the movements of the extremities in question. Fig. 98 shows the movements of a leg in running. The sets of dotted lines show at any particular moment the angle formed by each segment with the vertical, as well as the path followed by each joint.

In geometrical photographs, thanks to the great number of the images, the discontinuity of the phases almost entirely disappears, and the actual path followed by each part of the body can be seen represented almost as a continuous curve. These indications are most useful in studying movement from the point of view of dynamics, for by them the velocity as well as the acceleration of the body mass can be measured.

CHAPTER IX

CERTAIN MOVEMENTS IN MAN

From the Point of View of Dynamics

Summary.—Object of dynamics—Measurement of the forces which play a part in human locomotion—Traction dynamograph—Dynamograph for expressing the amount of pressure exercised by the feet on the ground—Combination of the dynamograph with a method of recording movements—The laws of ballistics as applied to the mechanism of jumping—Combined employment of dynamography and chronophotography—Mechanical work done in human locomotion; work in the vertical direction; work in the horizontal direction; work done in maintaining the movement of the lower limbs during their period of suspension—Relative amount of work done during different kinds of paces—Practical applications.

The movement of a solid body, and the force which produces it, are necessarily closely associated, so that knowledge of movement implies knowledge of force, and *vice versâ*. At the same time, in practice it is easier to measure force directly by means of the dynamometer.

Now, in human locomotion, the forces which are concerned are ever variable quantities, and to thoroughly understand each individual phase, a registering apparatus which affords a continuous record must be employed. Such an apparatus is called a "dynamometer," and indicates by the variations in its curve the amount of force which acts upon it at any particular moment.

Dynamometers are constructed on the principle that

an elastic body is distorted in proportion to the degree of force applied.

We have endeavoured to use dynamometers of uniform pattern throughout our researches on animal movements. And for that purpose we have always employed coils of indiarubber tubing, which were more or less compressed according to the external force applied. In consequence of this pressure, the contained air was more or less squeezed out into the chamber of a recording tambour.

The coils of tubing of which the dynamometer is formed are wound concentrically like the spring of a watch. The central end is closed, and the peripheral or free end communicates with the chamber of a recording tambour. The coil itself is glued on to a disc of cardboard.

This instrument goes by the name of "The spiral dynamometer." The tube used has a very fine bore with very thick walls, so that it can resist strong pressure without bursting. The distortion or compression is very regular, so that the lever of the registering tambour is practically raised to a height proportional to the force applied.*

By modifying this spiral form, we were able to construct a traction dynamograph (Fig. 99). The latter apparatus was used for measuring the force exercised by horses when differently harnessed. One of the ends was securely fastened to the vehicle and the other to the swing-bar. Traction on the part of the horses tended to approximate two discs, which compressed between them the turns of the spiral coil.† The air expelled

* To obtain greater accuracy the instrument may be empyrically graduated by applying a series of regularly increasing weights, and marking off on a scale the corresponding discursions of the lever.

† We proved by these experiments that, if the traction was applied through the medium of elastic traces, the gradual distribution of the shocks thereby occasioned effected a great economy in the force

from the spiral reached the registering tambour by means of a tube.

In most acts of human locomotion muscular force manifests itself in the form of pressure; for instance, this is the case when a man extends his legs from a previous position of flexion; as the legs become extended, the body mass is repelled in an opposite direction, because the feet, resting on the ground, offer a fixed point of resistance.

In walking or running, the foot presses on the ground

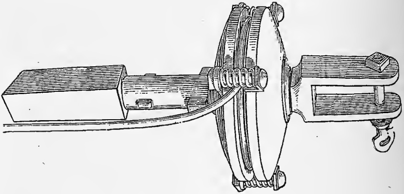

FIG. 99.—Traction dynamograph.

with a force equal to that which is expended in moving the body, so that by measuring at any moment the pressure of the feet on the ground, we also measure the force expended on locomotion. Our spiral dynamograph is a useful instrument for this purpose.

Dynamographic Platform for Registering the Pressure of the Feet on the Ground.—A series of spirals, similar to those previously described, are arranged on an oak platform (Fig. 100). One of these spirals is left

applied, and that this economy might even amount to 26 per cent. of the total motive force (Marey, *Trav. du Laboratoire*, 1875). Wüst found in similar experiments a saving of 22 to 33 per cent. in the work. Ringelmann has noticed an economy in work amounting to something like 50 per cent.

uncovered so that the tube of which it is made can be seen, the others are placed between cardboard discs. All the tubes which lead from these spirals unite in a common collecting-tube which communicates with the chamber of the recording tambour. A plate held in position by metal clips accurately covers all these

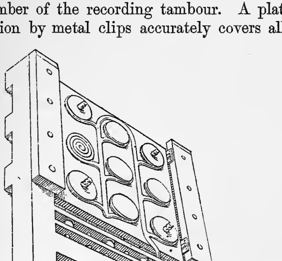

FIG. 100.—Dynamographic platform for giving a curve of foot-pressure on the ground.

spirals. Such is the general structure of the dynamographic platform.*

When a man mounts this platform the registering lever is raised to a variable height, and remains in the same position as long as he does not move. The discursion of the lever expresses the weight of the body; but however slightly the man may move, the

* *C. R. de l'Académie des Sciences,* October 8, 1892.

amount of vertical foot-pressure on the platform is altered in amount, and is recorded on the tracing by the lever. The following is the law which governs the variations in pressure :—

All muscular actions which alter the centre of gravity of the body in such a manner as to raise it augment the foot-pressure on the ground.

*All actions tending to lower the centre of gravity diminish the foot-pressure.**

The dynamograph which measures the force can be employed conjointly with an apparatus for recording the actual movement. It can be seen, then, that mechanical actions accomplished by living creatures obey general laws—amongst others those of ballistics.

Now, in order to determine the phases of a movement, two methods may be employed, either that of mechanical registration or that of geometrical chronophotography.

Mechanical Record of Movement.—Movements, such as we shall have to deal with, are generally too extensive to be directly recorded by means of a tracing needle. In jumping, for instance, the head may be elevated any distance between 30 and 50 centimetres in a vertical direction. This movement must be reduced to such proportions as can be registered on the surface of a revolving cylinder. This reduction can be effected by means of the *elastic-thread method* previously described (Fig. 29).

If a man stands on the platform of a dynamograph, and wears a very tight-fitting cap, the elastic thread may be fastened at one end to the cap, and at the other to a solid support by means of a clip (Fig. 101). This thread may be fixed near its upper end to the lever

* All effects which are produced during the performance of a movement are followed, when the movement is concluded, by counter effects in the opposite direction.

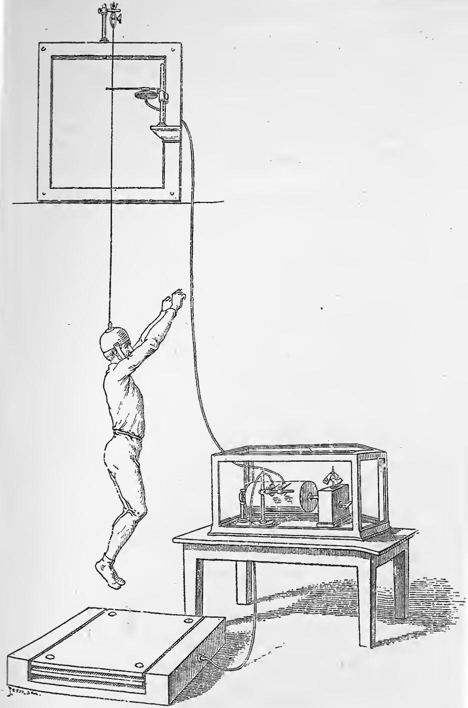

FIG. 101.—Method of simultaneously recording the foot-pressure on the ground and the changes in elevation of the body during a jump.

of a tambour. Two recording tambours register two curves on a revolving cylinder, one the curve of foot-pressure, and the other that of the vertical discursions of the head.

Examination of these curves, enlarged, if necessary, shows that in all respects the laws of animal movements conform to general laws—in this case to the laws of ballistics.

The areas of the curves which are described by the

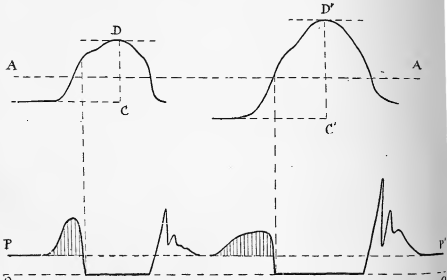

FIG. 102.—Superior curves; changes of height in the head during the jump. The ordinates DC and DC' are proportional to the height of the jump.
Inferior curves; pressure exercised by the feet on the ground. The shaded areas show the *quantity of movement* communicated to the body in the two jumps.

dynamographic needle express the exact equivalent of the force employed in the effort of jumping. And it is found that when two such areas differ, their ratio to one another is as the square root of the height jumped. If the area of the curves be the same, no matter what be the shape, the heights of the jumps must be the same. If two men of different weights jump the same height, the areas of the dynamographic

curves are in proportion to the weight raised. On comparing the curve of the height jumped with that of the dynamograph, it is found that it is not the absolute initial energy of the effort which conditions the height of the jump, but the amount or quantity of force expended, namely, the product of the force and the duration of the effort; in other words, the area of the curve.

Sometimes the lowest jumps correspond to curves which show great initial effort, but sustained only for a brief moment. In fact, areas of different curves, which represent jumps of equal height, may be infinitely varied; a violent and brief effort producing the same effect as one initially feeble but longer sustained.

Combined Employment of Dynamography and Chronophotography.—Mechanical registration of movement is not always feasible; for instance, in the case of a man walking, it is difficult to register all the movements of the different parts of the limb. Chronophotography comes to the rescue, and this method can be combined with the employment of the dynamograph. Let us suppose that we want to discover with what force the foot presses on the ground during the different phases of flexion and extension of the leg, provided, of course, that the foot never leaves the ground during the period under observation. The application of the chronophotograph combined with the dynamograph, at once suggests itself, the former recording the movements executed by the leg during half a step (Fig. 103), and the latter the degree of pressure exercised during the same period (Fig. 104).

It is now necessary to establish the connection between the various chronophotographic images and the corresponding elements of the dynamographic curve. For this purpose we must count in Fig. 103 the number of images which correspond to the phase

of downward pressure of the foot. It is found to be twelve. It is clear, then, that the dynamographic tracing, taken as a whole, corresponds to this total period occupied by the leg in its phase of downward

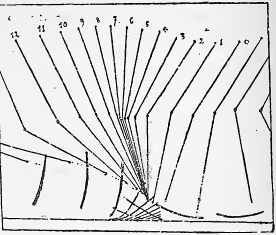

FIG. 103.—Geometrical chronophotograph of the movements of the leg in walking, during the period that the foot is in contact with the ground.

pressure, so we must divide the abscissa of this curve into twelve equal parts. If we draw the twelve corresponding ordinates, each of them will express the vertical force exercised by the foot on the ground for

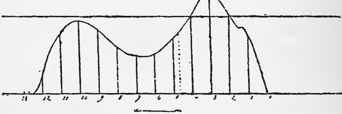

FIG. 104.—Dynamographic tracing to express the phases of pressure by the foot on the ground in walking.

the corresponding position of the leg. If these two sets of figures are correspondingly numbered in the tracings, comparison is greatly facilitated.

One can, if so desired, dispense with the dynamo-

graph, and measure the force expended from the data afforded by the geometrical chronophotographs; in short, when the body mass is known, as well as the position and movements of the centre of gravity,

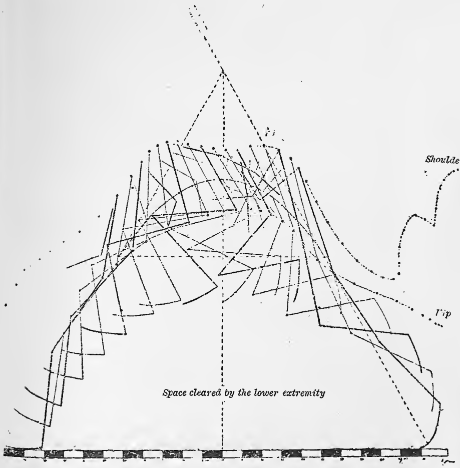

FIG. 105.—Geometrical chronophotograph of the movements executed in taking a high-jump.

the force expended on the movement can also be calculated.

Mechanical Work done by Man in Walking.—In view of the fact that it is possible to estimate the work done in jumping by means of geometrical chrono-

photographs (Fig. 105), it is easy to predict that the same method might be applicable in the case of various kinds of paces.

So far physicists have only calculated the amount of energy expended or gained by a man in walking along an inclined plane, in terms of the body weight lifted or lowered such and such a height. The first is a case of positive energy, and the second one of negative energy. The amount of energy expended in different directions is the product of the body weight and the height of lift, an amount which is expressed in kilogrammetres. Looking at the matter in this light, progress along level ground would require no apparent expenditure of energy, and yet it is accompanied with muscular exertion and consequent fatigue.

We thought it was possible to estimate approximately the mechanical energy expended in walking or running along horizontal ground by observing the movements transmitted in various directions to the body by the muscular actions involved. If the movements of the centre of gravity of the body could be followed in space, they would be seen to constitute a series of vertical oscillations in accordance with the movements of the feet. At the same time during each oscillation there is a certain movement of translation, sometimes at an increased and sometimes at a decreased velocity.*

Another way in which energy is expended is when movements are alternately communicated to the legs, movements which gravity might account for if they were, as the brothers Weber believed, comparable to oscillations of a pendulum. In practice, however, these movements usually require the help of the muscles.

The measurements (Fig. 106) of different movements

* We ignore as unimportant the movements of the centre of gravity which occur outside the vertical plane of progression.

of the human body and limbs in the act of walking have been obtained by means of chronophotography.

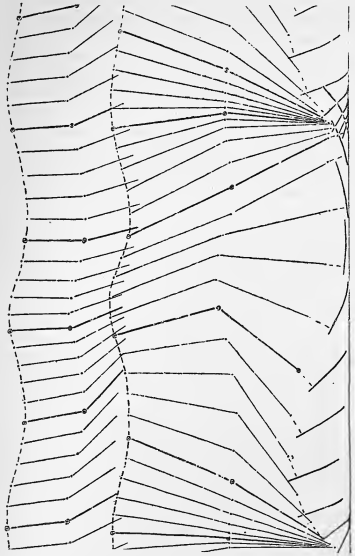

Fig. 106.—Geometrical chronophotograph of a man's movements when walking. The series of images must be read from left to right.

Three principal elements are involved in the work which is done during the act of walking on the level.

A. Vertical work.

B. Horizontal work.

C. Work expended on keeping up the oscillations of the legs during their period of suspension.

A. **Muscular Work done in a Vertical Direction.**— The movements of the head are practically the same as those of the centre of gravity. Now, the trajectory of the head-movements is an undulating curve (Fig. 107), which periodically reaches its maximum as the foot arrives at the mid phase of contact, and similarly reaches its minimum at the mid phase of suspension.*

The parallel and dotted lines (Fig. 107), which are tangents to the upper and lower limbs of this curve, afford a measure, by the distance which separates

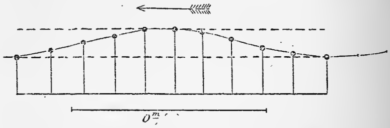

FIG. 107.—Vertical oscillations of the head when walking.

them, of the extent of the vertical oscillations of the body.

To measure the absolute extent of these discursions, a transparency of Fig. 107 is thrown on the screen, and enlarged by means of an optical arrangement to its actual dimensions, so that the extent of a vertical oscillation corresponds to the length of half a step measured on the ground. The work done each time the body is elevated or depressed can be estimated by multiplying the weight of the pedestrian by the vertical height which separates the dotted lines in the

* On the other hand, in running, the maximum corresponds to the period of suspension, and the minimum to the period of contact.

enlarged figure. So that, if the weight is 75 kilograms, and the amplitude of the oscillations 0·04 of a metre, each elevation of the body will represent 3 kilogrammetres of positive work, and each depression the same amount of negative work. As there are two double oscillations of this kind in a completed step, the muscular work corresponding to the vertical oscillation will be 12 kilogrammetres for each step.*

B. **Muscular Work expended on Movement in a Horizontal Direction in Walking.**—The velocity of the horizontal movement of the body is subject to periodic variations, and hence there must be periodic variations in the energy required, in proportion to the work executed in the different phases of foot-contact, whether this work be represented by movement or by resistance. These variations in speed are deduced from the degree of separation of the points on the trajectory, because these points are photographed at equal intervals of time, for instance, at intervals of $\frac{1}{50}$ of a second. The horizontal projection of these intervals allows one to construct the velocity curve of the horizontal movement by taking as ordinates lengths which correspond to the distances which separate the points, that is to say, which correspond to the velocity.

From the maximum and minimum velocities of the body mass, the corresponding measure of the energy expended can be deduced. The energy developed by muscles both in producing movement and in offering resistance is equal in each case to half the variation of the vital force. So that the total sum of these two forms of energy can never exceed the

* This estimate, namely, the body weight multiplied by twice the height of the vertical oscillation, is an inexact valuation, which does not really give the expenditure of muscular force: a certain portion of the energy seems to store itself up in the muscles during each period of descent, and to be liberated in the next phase of ascent.

amount of the whole force expended, that is to say, for the case in point, 2·5 kilogrammetres.

C. **Muscular Work done in moving each of the Lower Limbs during the Period of Suspension.**—The complicated movements of the lower extremities correspond to those of a pair of double-jointed pendulums in unstable equilibrium: they are, however, not only acted upon by gravity, but also by muscular contractions, while the point of suspension itself moves with a variable motion along a curvilinear trajectory.

The method employed for measuring the energy expended on these oscillations consists in measuring the moment of inertia of the lower limbs in reference to the axes of rotation, and by measuring on geometrical diagrams the angular velocity which they acquire. The result thus obtained is very small, 0·3 of a kilogrammetre for each step. Thus the most uncertain determination in these measurements is practically a negligible qnantity, and only very slightly influences the total amount of energy expended on each step.*

According to the estimates indicated above, the total amount of energy expended on a step is 9 kilogrammetres. But even the most exact measurement of the energy expended in any particular kind of pace is much less interesting than the study of the actual variations in the amount of work done as the pace is accelerated. If we calculate the total energy expended in fast running, the amount will be found to be very different from that expended on slow progression. The following are the estimates for running:—

* The practical importance of an exact determination of the energy is very great; it is also most desirable that all the papers we possess on this subject at the Physiological Station should be again studied by the most approved methods. This subject is worthy of the consideration of the greatest mathematicians.

	kilogrammetres.
Translation of the lower limb	3·4
Vertical oscillations of the body	2·3
Acceleration and remissions in velocity in the horizontal direction	18·4
Total ...	24·1

Thus the expenditure of energy in taking half a step on level ground varies according to the gait from 9 to 24 kilogrammetres. If account is kept of the number of steps taken in a minute in these two extreme cases, the expenditure of energy will be found to be, in slow walking 720 kilogrammetres, and in rapid running 6748 kilogrammetres, which represents about 12 kilogrammetres per second in the first case, and 112 kilogrammetres in the second.*

* We knew perfectly well that walking on level ground represented the expenditure of a certain amount of energy, and tried to estimate the exact amount. But that did not necessarily imply any difference of opinion between physicists and physiologists. If physicists only took account of the energy expended in walking when the road was inclined, it was because only in this case could they ascertain the exact amount of work done, namely, that required for lifting the body weight through a certain number of metres, or lowering it as the case might be.

But Coulomb knew full well that both in walking and in carrying burdens the muscles developed energy and did work, but not being able to reduce this expenditure of energy to the usual formula PH, he gave it the name of "Useful effect," (PE), that is to say, the weight multiplied by the distance traversed. In short, the measurement of energy in walking and running on level ground demands a complete knowledge of the movements transmitted to the body and limbs as the foot is lifted from the ground.

It was for physiologists to determine these movements, and as we have seen, chronophotography afforded them an excellent means of so doing.

In giving the above measurements of the work performed in walking, we said that they probably represented the maximum, and that their real value was perhaps something less. This is because in alternate movements in contrary directions there may be a certain storage of energy in the organs which execute the movements, and consequently there may be a certain suppression of energy which would otherwise be expended, and consequently in the succeeding action there may be a certain amount of restitution. To make our point clear, let us take the case of an elastic ball falling on a hard surface from a certain height. Let us suppose the ball weighs 100 grams, and that it falls through a distance of one metre. As the ball reaches the ground, the action of gravity will have produced work to the

Relative Amount of Work done in executing Various Paces.—If the values of the different factors constituting

extent of 100 grammetres. But let us go a little further. The ball in consequence will be flattened against the ground, and rebound to a certain height, 0·60 metre for instance. When the ball has reached this height, of the energy which has accrued from the effects of gravity, only 40 grammetres have been expended, because on letting it fall down again we shall find that there are 60 grammetres of energy left. These 60 grammetres, then, were recovered by the elastic force of the ball, which had stored them up.

Is there anything analogous, when at the end of a movement the antagonistic muscles tend to stop it; and will these muscles contribute anything towards the succeeding movement in the opposite direction? The following facts lead us to believe that there is such a restitution.

When one exerts one's self to jump and reach an object above one's head, if the first attempt is unsuccessful, sometimes the second succeeds.

Chronophotography shows that the second jump is always higher than the first. What is it that occurs in such successive acts? In the first jump, the total effort of the extensor muscles of the thighs and legs projects the body a certain height. In descending, these same muscles are contracted in order to break the fall, *i.e.* in order to counteract the energy generated by the body. Then these muscles are again contracted to project the body into the air a second time.

Now, since the height of the second jump is greater than the first, it must be admitted that the elastic force of the muscles which are contracted to break the fall, is added to the muscular action consciously brought into play for the second jump.

Now, is this elastic force of rebound due to a physical property of the muscles, or is it due to an additional expenditure of energy? Weber demonstrated that a muscle when in action acquired, by some intimate change within its fibres, a greater elastic force, and that it was this force which produced movement. The same thing happens, then, in a living tissue as in a steam-engine, in which the elastic force of a gas is converted into work.

Now, from the physiological point of view, in the second jump there was no obvious liberation of stored-up energy, but such liberation as there was must have been the result of intrinsic action accompanying all muscular contractions. If the body attained to a greater height in the second jump it was because the muscular energy was greater. We said, however, that in the first jump we exercised our muscles to the utmost extent. That is true, but it may not be by the most energetic, but by the most prolonged effort that we attained to so great a height in the second jump. It will be remembered that, in the experiments with the dynamograph, the "area of impetus," or the amount of movement communicated to the body, was proportional to the square root of the height jumped; and that the height of the jump did not depend on the mere height of the dynamographic curve, because the latter only expressed the degree of effort at one particular moment; the duration of the effort had also to be taken into consideration. For, as we mentioned, often the highest jumps corresponded to curves of the lowest amplitude.

the total energy expended on taking a step are compared, it is found that they are not equally (Fig. 108)

It is necessary, then, to know whether the impetus occasioned by the muscles has not lasted longer in the second than in the first jump.

In all contracting muscles, the elastic force starts at zero, and attains its maximum in a certain time. This results from the way in which the contraction is produced, namely, by a gradual summation of a series of contractions. Now, if we leave a crouching position to jump for the first time, our extensor muscles gradually contract, and these muscles will only produce their maximum effect at a more or less advanced phase of extension of the limbs.

In the second jump, on the contrary, when in breaking the fall we again assume a crouching position, our extensor muscles have already reached their maximum contracting force; and it is this maximum force which will continue to operate in raising us up again until we have left the ground. The body mass will have received the full effect of the muscular contraction during a longer period, and consequently will have received a greater "quantity" of movement.

A familiar example will help to explain the difference which exists, as far as intensity of result is concerned, between a force gradually developed throughout the duration of a movement, and another which acts with all its intensity during the whole period of a movement. When we wish to transmit an impetus to an object by extending a finger we give it a fillip. That is to say, by holding the last phalanx of the middle finger with the thumb, and strongly contracting the extensors of the finger, we let it go like a spring at the moment the maximum degree of extension is reached. The object is thus shot away with great force. The impetus would have been very much weaker if the middle finger had previously only been bent, and we had then suddenly extended it. In all alternating movements, the muscles work to better advantage than in simple movements. The brandishing of a weapon before striking has no other significance.

Now, since the work done by a muscle is the same, whether it is merely work of resistance or work represented as motion, we believe that, if we want to estimate the work done in walking, we are justified in doubling the value of each of the component factors of the work expended in maintaining the oscillations of the body and limbs. If we said that the estimate thus obtained probably represented the maximum, it would be because the vital energy transmitted to the body in the horizontal direction, and that transmitted to the legs at each oscillation, are not totally expended on the movements, part being lost in the form of shocks imparted to the ground. Vital energy is perhaps stored up in real elastic structures of the body, such as tendons.

Veterinary experts have made a special study of the energy lost by the hoofs striking the ground when a horse is travelling at a rapid pace. They maintain that the flexor of the solitary toe which constitutes the foot of a horse, is made to a great extent of elastic tissue. It possesses in consequence a physical property by means of which a more or less important part of the vital energy lost in falling on the feet is to some extent returned in the form of energy.

influenced by the rate of progression. Thus, during slow walking, the energy expended in vertical oscillations is relatively greater than when the velocity of horizontal translation is increased; in rapid running, the reverse is the case. It is necessary, then, to follow through all their phases the variations which the

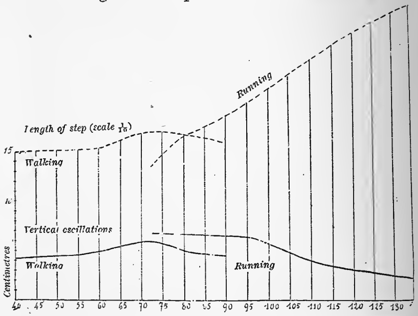

FIG. 108.—Variations in the vertical oscillations of the body in walking and in running. The rate of step varies between 40 and 130 per minute. Comparison between the curve of oscillation and that of the length of stride.

component factors of the work undergo when under the influence of a gradual acceleration.

In order that these variations might be clearly understood, they have been represented (Fig. 109) in a graphic form. In constructing these curves, the number of steps executed in a minute has been numbered off on the abscissa. The corresponding ordinates were made proportional in length to the sum of all the factors

This subject deserves re-investigation. It would be interesting to discover whether tendons in man possess this valuable property to any noticeable degree, and, if so, whether it is retained throughout life.

of the work. Whatever was the number of steps per minute, the value was marked off on the ordinates from below upwards always in the same order.

1. The value of the work done in moving the lower extremity.

2. The value of the work done in the vertical oscillation of the body.

3. The work done in accelerating and slowing the horizontal movement of translation.

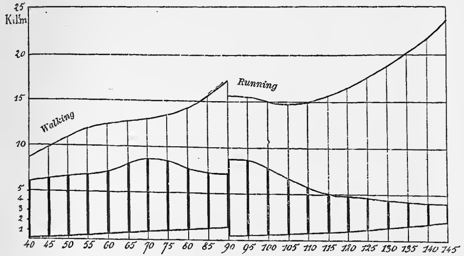

FIG. 109.—Curves of the different elements of the work performed in walking and running, the rate of step varying from 40 to 145 per minute. The scale to the left of the figure indicates the number of kilogrammetres expended on each step. Each of the ordinates is composed of three separate elements, representing the value of each of the component portions of the total work. The lowest element corresponds to the work performed by the oscillations of the leg. The middle (the thick line) represents the vertical oscillations of the body. The superior one corresponds to the degree of acceleration and slowing down of the body mass.

On the curves represented in Fig. 109, the different factors in the work apparently vary in an extraordinary fashion; but these variations can easily be accounted for by certain considerations from the point of view of kinetics or dynamics.*

* To quote from a communication made to the Académie des Sciences, by M. Demeny and ourselves, November 9, 1885 :—

A. *Variations in Work done in moving the Lower Limbs.*—The work

Practical Applications.—The data afforded by these measurements may be put to practical use, for they

performed in executing these movements obviously increases in proportion to the degree of acceleration of the rate of step; but a fact which is at first surprising is that for the same number of steps per minute a runner expends less energy than a pedestrian. Thus, at ninety steps a minute, a man would expend in walking 1·4 kilogrmtrs in the movement of the lower extremity, while a man in running would only expend 0·5 kilogrmtrs. And yet the actual speed at which the legs move in running is greater than in the former case.

This difference is because the speed at which the limbs move in reference to the body should be considered by itself in these estimates. Now, the speed is greater in walking than in running.

Indeed, for an equal number of steps per minute, the duration of oscillation of the lower extremity is greater in proportion as the period of contact of the foot is less. The period of contact in walking occupies more than half the total time occupied in taking one step. In running, on the contrary, the duration of contact is always less than half, and as the angular displacement of the lower extremity is practically equal in the two cases, it follows that the velocity of movement of the legs will be less in running, because the period of oscillation will be of greater duration. A physiological result of this inequality in the duration of oscillation of the limb in different paces is the intuitive tendency to begin running as soon as the rate of walking becomes too fast. This is one of the numberless examples of our natural instinct to expend the least possible effort in muscular actions.

B. *Variations in the Work done by the Vertical Oscillations of the Body.*—This factor in the work does not increase regularly with the rapidity of footsteps. In walking, the work rapidly increases between 55 and 70 steps per minute and then decreases. In running, it is very great when the number of steps per minute is small, and diminishes as the rate becomes greater. This factor in the total work done depends on the weight of the body and the amplitude of the vertical oscillations. The difference in the amount of work performed in various paces bears a direct relationship to the amplitude of the above oscillations.

Photographic and mechanical records of the vertical oscillations show that in walking there is a relationship between the length of stride and the amplitude of the vertical oscillations of the body, and since we have proved that the length of stride increases with the rapidity of the step up to 70 steps per minute, and then diminishes rapidly as the step is further quickened, it naturally follows that the work corresponding to these different steps varies in the same manner.

In running, the work done is greater when the rate of step is slow, and then decreases indefinitely. The corresponding vertical oscillations vary in the same way. The body being suspended in the air during part of the step in running is no longer constantly influenced by the changes in the directions taken by the limbs. Consequently, it is the duration of the vertical oscillation which regulates the amplitude. If the rate of step is slow, the body must be elevated very high so that it may fall slowly on to the limb which comes in contact with the ground.

indicate, according to the object in view, the best way of utilizing muscular force in walking or running: whether it be to traverse the greatest distance with the least expenditure of energy, or whether it be to cover a certain distance in the least possible time. Attention should not only be directed to the kind of pace, running or walking, for instance, but also to the number of steps to be taken in the minute.

It has already been pointed out (Fig. 109) that, in walking rapidly, from 70 steps per minute onwards, the expenditure of energy rapidly increases, and that in running the total energy is considerably greater when the number of steps per minute are few, but commences to diminish when the frequency of step increases, and finally again increases. There is, then, for each pace an optimum rate of steps per minute, which corresponds to the point at which the velocity increases proportionately faster than energy is expended.

There are other points to be considered in choosing a pace. Energy must not be exhausted so quickly that the muscles have not time to recover from the effects of fatigue. A long walk, in which a great deal of energy has been expended, may be borne with impunity, while rapid running would soon exhaust the muscular strength, although the total expenditure of energy may be much less.

As the studies just described have only been made in

If the rate of step is rapid, a slight extension is afforded to the oscillations by the short duration assigned to it. Thus, in walking, the amplitude of the vertical oscillations of the body is related to the length of step; it is independent of the length in running; in fact, an inverse relationship can almost be detected.

C. *Variations in the Amount of Work done in the Acceleration and Slowing of the Horizontal Translation of the Body.*—This factor in the work increases fairly regularly with the rate and length of the step. In running, it assumes considerable proportions, although the absolute variations in speed are slight. This is because the gain or loss of vital energy is in proportion to the difference of the squares of the maximum and minimum velocities of translation.

a small number of subjects, and those generally of good physique, the results cannot be generally applied to the average man—to a soldier, for instance.

The officers in our army have taken an interest in these researches, and have furnished us with the means of repeating them on a considerable number of soldiers. The influence of the figure, the weight of the body, the uniform, and the weight carried, had all to be taken into consideration. With the co-operation of M. Demeny and Lieutenant R——, we carried out these researches, and our first results were reported to the Minister of War.

CHAPTER X

LOCOMOTION IN MAN

From an Artistic Point of View

Summary.—Influence of Photography on Art—Different characteristics of ancient and modern works of art—Photography catches the real attitude—Importance of representing the correct outline of muscles during different actions—Photographs taken from different points of view—Photographs taken from above—Study of the most characteristic attitudes in a movement—Importance of having a series of photographs from which to choose the most expressive attitude—Analysis of facial expression—Choice of the best method for procuring artistic results.

Photography has already rendered great services to Art. Some artists openly admit it, and many more make use of it, as may readily be seen by comparing recent works with those of earlier date. It is more especially instantaneous photography that has had such an influence, because it has afforded reliable pictures of phenomena of very short duration, such, for instance, as of sea waves, or even of the attitudes of men or animals during the performance of the most rapid movements.

We are not qualified to speak of Æsthetics, still less to discuss the question as to whether Art has the right to represent violent actions, or whether it should restrict itself to more reposeful attitudes. In the latter, the characteristic expressions are easier to reproduce from living models; but, as a matter of fact,

it is incontestible that, in ancient times, as well as at the present day, artists have often represented movement of the most active description, such as running or fighting. Now, if old masterpieces are compared with those of recent times, one is struck with this difference between them, that the modern attitudes are quieter and better poised, so to speak, while in ancient works of art the figures sometimes appear in positions of unstable equilibrium. Fig. 110, taken from a Greek

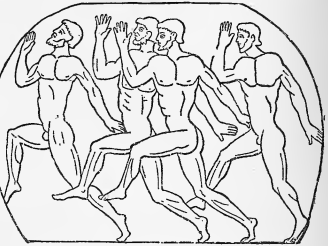

FIG. 110.—Ocydromes or swift-runners (from a Greek vase).

picture, is an example of this kind. Every one can think of some modern picture representing a similar subject. In sculpture especially, the action of running is differently represented nowadays. The supporting leg is generally seen vertically extended beneath the centre of gravity of the body, while the other leg is in an extreme position of elevation behind.

Nature herself may fairly be appealed to in deciding between these two methods of representing the same action. Instantaneous photography is an excellent means of showing the actual attitudes assumed. There

is no doubt about the decision. Fig. 111, for instance, shows that a man in running assumes at certain moments positions exactly like those represented in the old masterpieces.*

FIG. 111.—Instantaneous photograph of a runner: the position of the legs is the same as that of the man on the extreme left of the foregoing illustration.

It is quite easy to prove that runners never appear in the positions adopted by certain modern artists,

* One sometimes sees on a Greek vase a group of runners in the most curious positions. It is a perfectly familiar fact that a man in running or walking always swings the corresponding arms and legs in opposite directions. The corresponding arm and leg move, so to speak, in diagonal association. Now, on the Greek vase the arm and leg belonging to the same side are represented as moving in the same directions. Now, was this style of running, which is somewhat suggestive of the ambling of quadrupeds, really practised on the ancient race-course? or is it a mistake on the part of the decorator of the vase? This is a question we are unable to answer. Such a style of running is quite different from that now practised; yet at the same time it does not appear physiologically impossible. It is certainly a question worth considering.

who seem to forget that one of the characteristics of running, and even of walking, is to maintain a continuous position of unstable equilibrium. We must not, however, spend time on these reflections, for by criticizing the details of works, which are excellent in other respects, we may expose ourselves to the warning, "Ne sutor, ultra crepidam." We will only remark that among the infinite variety of attitudes shown by chronophotography in registering all the phases of a movement, there are certainly

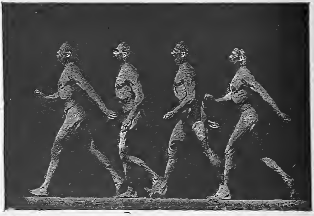

FIG. 112.—A man walking; successive positions afforded by chronophotography on fixed plates.

some which might be accepted by artists without transgressing the laws of æsthetics, and an interesting variety might be given to such representations. Thus, in Fig. 112, in which a nude figure is represented as walking, a series of attitudes is shown, amongst which several could be introduced into a work of art; and so with many other series of the same kind.

In these pictures artists would also find a faithful expression of the action of the muscles, which show the conditions of contraction or relaxation by the degree of prominence. Now, these two opposite conditions of the muscles are closely associated with each

phase of the movement in which they take part. The standing out of muscles in action has, so to speak, an individual expression, just as is the case with the facial muscles, and if most subtle physiological knowledge could be applied in all cases, it might be said that the modelling of a limb could not only express the action of the time being, but could suggest to a certain extent its immediate successor.

Some interesting experiments of M. Demeny show

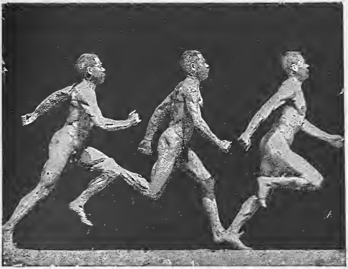

FIG. 113.—Chronophotographic illustration of a runner.

that the extension of an arm in striking, if it is to be complete, must be accompanied by the total relaxation of the flexor muscles. The latter muscles, however, come into play, if the movement of extension is to be arrested. As, for instance, in the case of a man preparing to strike, without the actual intention of delivering the blow.

In the four following figures, the expression of the outstanding muscles varies according to the nature of the preceding movement, although the final attitude

of the arm is the same. Thus Figs. 114 and 115 both represent a semiflexed arm, but in the first the outstanding biceps shows that a movement of flexion is in process of production, and in the second it is the triceps (extensor muscle) which stands out most

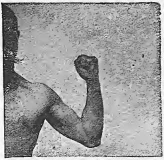

Fig. 114.—Flexion of an arm.

Fig. 115.—Extension of an arm.

markedly, while the biceps is flattened. The attitude here represented corresponds to a phase in the extension of the limb.

In alternating movements, the antagonistic muscles come into play. If extension of the arm is to be

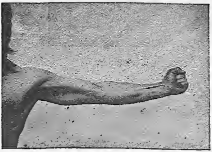

Fig. 116.—Alternating movements of flexion and extension.

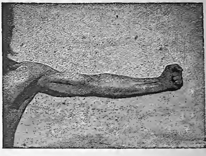

Fig. 117.—Single movement of forcible extension (delivery of a blow).

followed by flexion (Fig. 116), although the triceps is the muscle directly concerned in the movement, the biceps is also contracted, partly to arrest the momentum of extension and partly so as to be ready

for immediate action. If the blow is delivered in a definite manner, as, for instance, a blow with the fist (Fig. 117), the moment the limb is extended the muscles have no more to do, and so relax themselves.

For the purpose of sculpture the model should be viewed from different aspects. By taking chronophotographs of a moving man from some point above his head (Fig. 118), a horizontal projection is obtained which shows the exact contour of the body. This photograph, as well as those taken from different angles, would doubtless be very useful to the sculptor.*

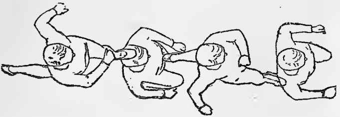

FIG. 118.—Chronophotograph of a runner taken from above. (Horizontal projection.)

Quite apart from any artistic object, it is often necessary to have recourse to various forms of modelling to represent the attitude of man, or the movements of animals, in the three dimensions of space. We have often utilized this method for determining from several photographs, taken simultaneously, the attitude of a bird's body and wings during the act of flight. We only wish that some artist would devote his talents,

* It was proposed some time ago to produce, under the name of photosculpture, a method for mechanically reproducing a model of an individual.

The person was placed in the middle of a circle, on the circumference of which were arranged a row of cameras. Each of these cameras took at the same moment a photograph of the figure which was thus represented from various points of view. Each photograph was enlarged to a convenient size and transferred to a metal plate and converted into a sort of mould. On pressing some plastic material on to the plate, a rough model was obtained, absolutely exact as far as attitude was concerned, and one from which the sculptor could execute a properly finished copy.

by the aid of such photographs, to the representation

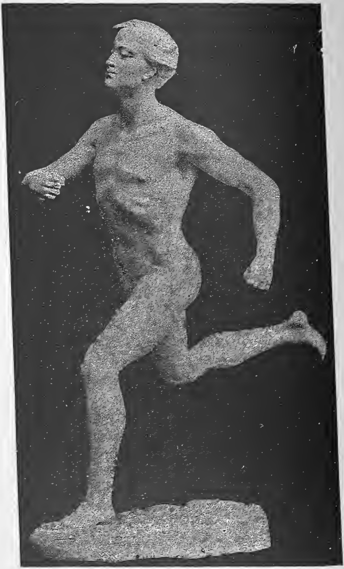

FIG. 119.—Statuette made from chronophotographs.

of men in the act of running just at the moment when the feet come in contact with the ground.

M. Engrand, wishing to work on these lines, made the statuette represented in Fig. 119. The attitude is very different to those usually presented in Art; the foot which touches the ground is well in advance of the centre of gravity, so that the choice of such an attitude perhaps creates a practical difficulty, inasmuch as the figure is in unstable equilibrium. In order, however, to reconcile this with physiological knowledge, an attitude should be chosen in which the centre of gravity lies exactly over the point of support. At this moment the elevated leg is never behind the leg which supports the weight of the body, but lies directly across it. This attitude is seen in all human paces, in walking as well as in running, with this difference, that in walking the legs are much less flexed at the joints.

Study of the most Characteristic Attitudes in a Movement.—In representing a movement, for instance, one of a man, an artist rightly attempts to reproduce a phase which is visible to the eye. It is usually the preliminary or the final phase which can be best appreciated. When a machine is in motion, there are certain parts of it which are only visible when they reach their dead points, that is to say, for the brief moment when the direction of movement is changed. And this is also the case with certain movements in man. Some attitudes are maintained longer than others. Now, chronophotography on fixed plates could be used to determine these positions. They are recognizable in the photograph as the ones which have left the most intense impressions on the sensitized plate—in fact, as those which have had the longest exposure. Thus in Fig. 120, which represents a fencer in the act of lunging, most of the impressions are indistinct or confused, while two of them stand out as well defined positions. The first of these is when the

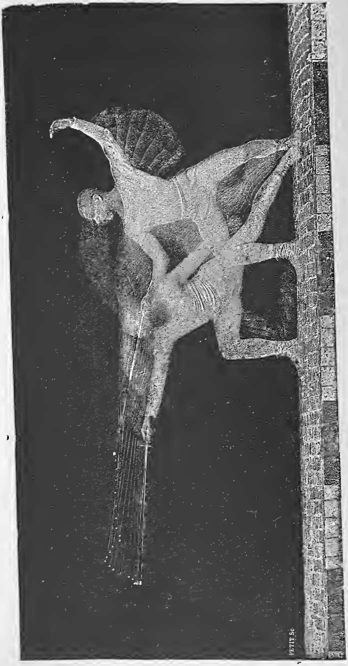

FIG. 120.—A sword thrust. (From a chronophotograph on a fixed plate.)

man is preparing for his thrust, and the second is when his arm is extended to its utmost limit after he has executed the lunge.

Fig. 40 was taken from two equally good photographs of a boxer.*

In all possible actions, such as pulling a string, lifting a weight, turning a wheel, pushing a wheelbarrow, etc., there are some attitudes which last longer than others, and which may be called "positions of visibility." † Chronophotography would determine these with the greatest precision.

Importance of having a Series of Photographs from which to choose the most Expressive Attitude.—If a movement had always to be represented in its slowest phase, Art would be beggared of all originality of expression. We should then have a sort of catalogue of stereotyped attitudes, just as we have laws of anatomical proportion. Hampered by these limitations, the artist would lose all individuality. He ought, on the contrary, while taking Nature as his model, to make an independent choice between the objects offered to him. Among the many photographs we have obtained, some have struck us as particularly expressive, and we believe that they are the very ones that an artist would select.

In a series of photographs that we took of a man striking a forcible blow with a stick, there was one that particularly appealed to us. At the moment of supreme effort almost every muscle in the body stood out in forcible contraction. This would not occur in a quieter action, or in a more limited movement.

* These two figures were borrowed from an article on physical exercise by M. Demeny, illustrated by means of chronophotography (*La Nature*, October 11, 1890).

† With regard to the locomotion of quadrupeds, we shall show, further, that in the horse, for instance, these phases of slow motion never occur in all the limbs at once.

A slow action, such as that of a man sitting down on the ground and then stretching himself out in a recumbent position, would present no such general muscular contraction.

Chronophotography of Facial Expression.—With the camera which we used, although it has only one objective, a subject can be photographed at a near distance, and show no alteration in perspective, however long be the series of photographs. It is the only kind which, up to the present, has been capable of affording a series of photographs which shows in all their details the changes in facial expression, the various movements of the hands, and the different positions of the feet in walking.

It would be interesting to follow in this way all the transitions between a scarcely perceptible smile and a hearty laugh, and to catch the characteristic expressions of astonishment, anger, and other emotions. The great difficulty is to find a subject capable of giving these various expressions in a perfectly natural manner. Most people would only produce a grin or a grimace. Clever actors would no doubt succeed better in assuming the various emotional expressions; and the method might even be useful to them in their own studies. But that which is rendered to perfection by chronophotography is the movement which accompanies the act of articulation. M. Demeny has paid special attention to this extension of our method, and he has met with immense success. With strong and well-directed light he has shown the way the tongue moves in the articulation of consonants. His researches are of value from a phonetic point of view, and practically it ought to be of service in the teaching of deaf mutes. One ingenious method for instructing deaf mutes consists in teaching them to read the various movements of the lips in producing different

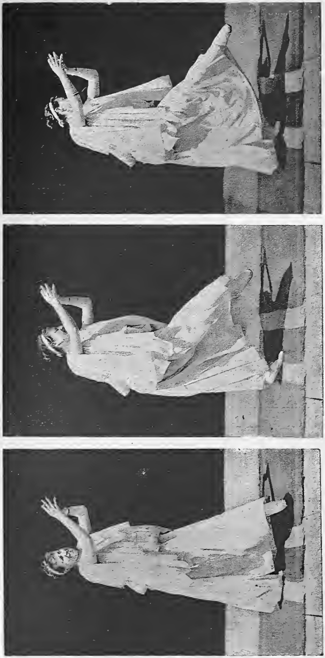

FIG. 121.—Successive attitudes of a Greek dance, the influence of the movement on the fall of the draperies (simili-gravure).

words, and to carry on a continuous conversation in this way. M. Demeny was very anxious to know whether deaf mutes would be able to make out a conversation carried on by means of a series of photographs. The result of his experiment was most satisfactory. The deaf mutes read from the chronophotographs the words which had been uttered. It is unnecessary here to remark that without special teaching this novel kind of writing cannot be deciphered.*

And now from an artistic point of view. What is to be the outcome of this new method of reproducing the movements of speech? Painters have hitherto apparently paid no attention to the subject.

In the most animated scenes, it is the general expression of the features that conveys an idea of what the individuals are supposed to be saying, and the same holds good in sculpture. Rude has twice attempted to represent, if not actual words, at least a cry of imprecation or command.

We wanted very much to know what sort of expression a man's features would assume when he uttered a loud exclamation. The attendant at the Physiological Station was the subject of our experiment. He was placed in front of the objective, and told to shout at us several times in succession at the top of his voice. The series of photographs thus obtained showed the periodical repetition of the facial expression, but so curiously contracted were the muscles of expression that the appearance was rather that of an ugly grimace; and yet simply to watch him there was nothing extraordinary in the man's expression.

The peculiarity of the photographs was due to the fact that they caught exceeding fleeting expressions of the face—movements which were really ones of

* *C. R. de l'Académie des Sciences*, t. cxiii. p. 216, 1891.

gradual transition, and none of which were seen as isolated expressions.

Let us place the series of photographs in a zootrope and watch them as they pass in succession before the eyes as the instrument revolves at a convenient speed. All the strangeness then disappears, and we only see a man articulating in a perfectly natural way. What does this fact imply? Is it not that the ugly is only the unknown, and that truth seen for the first time offends the eye? We are often faced by this question while examining instantaneous chronophotographs of horses moving at a great pace.

These positions, as revealed by Muybridge, at first appeared unnatural, and the painters who first dared to imitate them astonished rather than charmed the public. But by degrees, as they became more familiar, the world became reconciled to them, and they have taught us to discover attitudes in Nature which we are unable to see for ourselves, and we begin almost to resent a slight mistake in the delineation of a horse in motion. How will this education of the eye end, and what will be the effect on Art? The future alone can show.

The Fall of Draperies.—The arrangement of draperies played an important part in ancient Art. In the masterpieces, whether of painting or sculpture, which have been handed down to us, the folds in the materials are so conscientiously represented that they have served as exact patterns of the different Greek and Roman vestments. Our colleague Heuzey has interested himself in these questions, and has inaugurated a special course at the École des Beaux Arts, in which young artists are taught how to drape their models correctly and gracefully.

Fig. 121 shows a woman dressed in the Greek style, and indicating the pose of the body in an ancient

dance. Fig. 122 shows the same woman draped in a cloak, and turning round in a sort of valse. M. Maurice Emmanuel, who is bringing out an important work on the dances of antiquity, asked us to take instantaneous photographs of certain attitudes, such as he noticed on some of his bas-reliefs and Greek vases. On looking at these photographs one cannot help recognizing a sort of general suggestiveness of

FIG. 122.—Imitation of the attitudes of a Greek dance, and of the fall of the drapery.

the particular movement of the dance by the fall of the drapery.

Even the successive phases of a dance may be followed in a series of chronophotographs, but the narrow limits of this book only allow us to offer a few examples (Fig. 121).

It is easy to see what a variety of attitudes could be obtained on a long film. And these could show

all the phases of a performer's movements, and afford the artist a choice of more or less expressive and graceful positions.

Choice of Method for obtaining Artistic Results.—Both kinds of chronophotography answer excellently for securing artistic results. Figs. 112 and 113, taken on a fixed plate, are of interest, for they clearly demonstrate the uniform transition from one attitude to another. Photographs taken on a moving plate can be more numerous for the reasons previously given in Chapter VII., and therefore offer a greater variety of attitudes, and, further than this, they can be taken with any kind of background. And although we have generally adopted a black background, that is only because the figures stand out more sharply.

If a light background is used, some of the outlines of the figures stand out very poorly. In using a dark background, care must be taken not to let the light fall exclusively on one aspect of the model, or else the parts in shadow may be confused with the background. On the other hand, in using a light-coloured background, if the model is in full sunlight, violent shadows will be thrown on to the field, and look so fantastic that it is as well to avoid them. This can be done by placing the background at some distance from the model so that the shadow fails to reach the distance, and is lost in the ground. Skilled photographers have a thorough knowledge of the conditions of light, and are therefore able to photograph their subject to the best advantage.*

* It is not only the material on which the prints are obtained that influences the artistic merit of the picture, the polish on some photographs may render the subject difficult to distinguish under certain conditions of light. As to reproductions on paper, the different methods are of unequal merit. In typography, simili-gravures give some of the best effects, but they are not so good as those obtained by proof impressions with thick ink.

CHAPTER XI

LOCOMOTION OF QUADRUPEDS

SUMMARY.—Chronography shows how the feet rise and fall in the different paces of a horse—Transition or passage from one pace to another—Representation of the attitudes in all paces of a horse, as shown by chronography and hoof-marks—Comparison between diagrams obtained by these methods and those obtained by instantaneous photography—Chronophotography applied to the representation of a horse in motion—Artistic representation of the horse among the ancients—Locomotion of the horse from the physiological point of view—Geometrical chronophotography of the movements taken as a whole—Individual movements of the foot and fetlock.

OF all four-footed animals, the locomotion of the horse is best understood. For some time past specialists have applied themselves to the study of equine paces, both regular and irregular, and have attempted to define the characteristics of each pace, according to the sequence in which the feet strike the ground; but, as we have already remarked, however observant the human eye may be, its scope is still very limited. This is proved by the varied opinions of different authors concerning the characteristics and mechanism of certain paces of the horse. The graphic method has, however, in our opinion, been useful in determining the character of each pace with great exactitude, and in showing how the transition occurs between one pace and another.

The difficulty of observing the different paces consists in having to follow the movements of all four

limbs at one and the same moment. The question is, however, largely simplified, if the quadruped is looked upon as two bipeds walking one behind the other, and presenting various combinations of steps according to the individual sequence of each. If two men take up such positions, the one in front will reproduce the movements of the fore feet of a horse, and the one behind those of the hind feet. Both will execute in a given time an equal number of steps, but by varying the sequence they can imitate all the paces of a horse.

In Chapter I. we gave an example of the kind of diagram which is used to represent the successive rise and fall of the fore and hind limbs of a horse, whether at an amble, a walk, a trot, or a gallop.

Fig. 123 presents a complete table of all the paces, and shows how one is derived from another. In the order in which these diagrams are arranged, beginning from the top in Fig. 123, each differs from the preceding one, inasmuch as the hind feet slightly anticipate the movement of the front. The description under these diagrams suffices in itself to show how authors disagree in the definition of each pace.

We only give a brief account of these chronographic researches, because we merely want to give a general idea of the principles of the method.*

To demonstrate the value of this method suffice it to say that these experiments have put an end to most of the disagreements relating to equine paces, and we believe that the results of our investigations are now universally accepted.

Transition or Passage from one Pace to Another.—It is very difficult for an observer to realize how an alteration of pace is effected; chronography demonstrates this very clearly. This is one of the greatest practical advantages of the method. Let us compare the paces

* See, for analysis of paces, *La Machine Animale*, pp. 140–186.

of the two men walking one behind the other. The

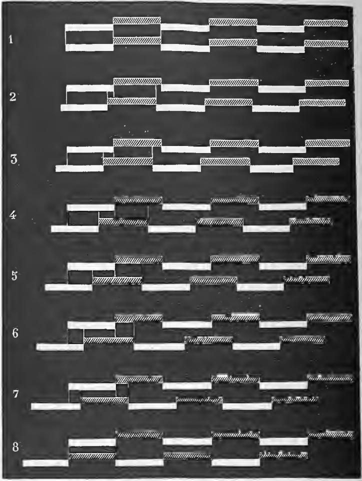

FIG. 123.—Synoptic chart of a horse's paces according to different authorities.

No. 1. Ordinary amble according to all authorities.

No. 2. { *Amble rompu* (racking amble), according to Merche. *Pas relevé*, according to Bouley.

No. 3. { Ordinary going pace of a horse, according to Mazure. Racking amble, according to Bouley. *Traquenard* (racking pace), according to Lecoq.

No. 4. Ordinary pace, according to Lecoq.

No. 5. Ordinary pace, according to Bouley, Vincent and Goiffon, Solleysel, Colin.

No. 6. Ordinary pace, according to Raabe.

No. 7. Loose trot.

No. 8. Ordinary trot. (In the figure, it is supposed that the animal trots without ever leaving the ground, which only rarely happens. The notation only takes into consideration the rhythm of the beats.)

steps more or less alternate or correspond, and the

united movements reproduce the gait of a quadruped. Now, if one of these men for a moment slackens or hurries up his rate of walking, and then continues as before, the relationship will be changed, and the net result will be an alteration in the quadrupedal pace.

FIG. 124.—Transition from walking to trotting. Chronographic record, read from left to right.

This is why a soldier, who in marching has got out of step, gives a little hop to regain the time.

We have recorded some of these transitions by means of chronography. Thus Fig. 124 represents such a transition from walking to trotting.

Independently of the general acceleration of *beat*,

FIG. 125.—Transition from trotting to walking.

this transition is effected by an anticipatory movement on the part of the hind feet, thus the fall of the left hind foot PG, which in walking occurred practically during the mid phase of rest of the right fore foot AD,

FIG. 126.—Transition from trotting to gallop (three-time).

gradually assumes a position less and less in advance of the fore foot, and finally the two coincide. At this movement a trotting step is established. That the

diagram may show more clearly the gradual change that occurs in the sequence of these two diagonal footfalls, the lines which represent them on the diagram are united, so as to mark the commencement of each footfall. The connecting-lines, at first widely

FIG. 127.—Transition from a gallop (three time) to a trot.

separated, approach nearer and nearer together, and ultimately unite as the diagonal footfalls become perfectly synchronous, a characteristic of the trotting step.*

The Successive Positions of the Feet indicated by their Impressions on the Ground.—Although chronography may be a perfect method for expressing the actual

* Other transitions have been observed in the same way. The transition from trotting to walking is effected by an inverse procedure to that which has just been described. It is brought about by the gradual hurrying up of the movements of the fore feet, and this is accompanied by a general slackening in speed (Fig. 125). The dotted line uniting the diagonal beats of the left feet, is at first vertical, and expresses that in trotting these beats are simultaneous. This line becomes more and more oblique during the process of transition, and thus shows how the synchronism ceases, and that there is a delay on the part of the hind feet.

The transition from trotting to galloping is very curious. Fig. 126 at the commencement shows that the trot is already rather broken, the dotted lines uniting the diagonal beats AG–PD is at the start rather oblique, and indicates a slight delay on the part of the hind foot. This obliquity increases, but only in the left diagonal beats. The right diagonal pair, AD–PG, remain synchronous, before and after a galloping pace has been established. This transition is not effected by the delay of the hind foot alone, but also by the advance of the fore foot, so that the two diagonal beats, which in trotting were synchronous, now have an interval between them equal to the whole galloping step. This interval corresponds to the long period of silence noticed in ordinary galloping.

The transition from galloping to trotting is effected by an inverse process (Fig. 127). The transition from a gallop in four-time to a gallop in three-time is effected by a gradual anticipation in the beats of the hind feet.

sequence in which horses' feet strike the ground, it gives no information as to the position on the ground struck by the feet.

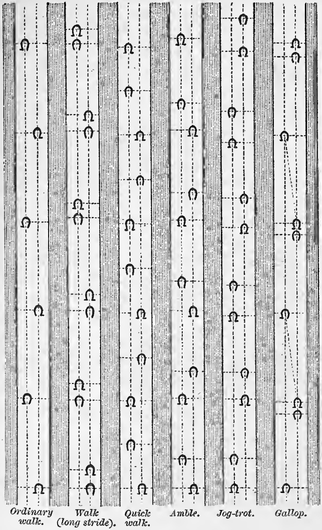

FIG. 128.—Table of the track of a horse performing different paces.

The tracks or footprints left on the ground by the horse give this information in an exact manner. The

tracks have been carefully studied in equitation. Horses have been shod with different-shaped shoes, so that each hoof might leave on the ground a mark that could be recognized. Fig. 128, compiled from diagrams borrowed from different sources, shows the corresponding tracks of the different paces of a horse.*

In the track left by the feet at a walking pace, the hind feet are placed in the impressions left by the front, the right hoof-marks exactly alternate with those of the left feet. The distance between two impressions on the same side is practically equal to the height of the horse at the withers.†

The hoof-marks are not exactly superimposed in walking except when the ground is level, and the animal moves at a certain rate. Going uphill, the marks of the hind feet are generally behind those of the fore feet. They may reach beyond them in walking downhill, with a result rather like that of ambling. In the hoof-marks left by a horse at an amble, the impressions of the hoofs on the same side are not superimposed. The marks of the hind feet are far in advance of those of the fore feet.

The hoof-marks left in trotting resemble those of walking, except that there is a longer interval between the steps. However, in slow trotting, the hoof-marks

* In this table the prints of the right and left feet can be recognized from their position on the right or left of the dotted and parallel lines. The impression left by a fore foot is that of an ordinary horse's hoof, that by a hind foot has two little cross-bars at the heel. The double impression, that is to say, when the hind foot occupies the place vacated by the fore foot, shares both these characteristics, but has only one cross-bar.

† Raabe held that there was a constant and absolute equality between the height of a horse and the distance between two consecutive hoof-marks. Most specialists question so exact a relationship. In any case it could only obtain in certain steady paces; horses, like human beings, lengthen their stride as the pace is accelerated (see chap. viii., p. 132).

are not superimposed, and the hind foot does not reach the impression of the fore foot.*

Representations of the Attitudes assumed by a Horse in its Different Paces as shown by Chronography and the Footprints.—It ought to be possible, by combining the two ideas of time and space which we already

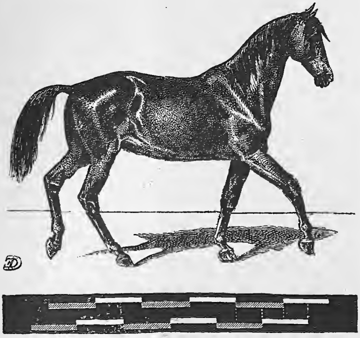

FIG. 129.—Representation of a walking horse, designed from a chronographic chart and from the footprints.

know, to represent with accuracy the attitude of a horse at any given moment during one of its paces. Vincent and Goiffon were also of this opinion; their remarkable book on the subject was designed as much for artists

* These tables are taken from a treatise on the subject by Vincent and Goiffon; those of galloping are borrowed from Curnieu, the latter are reduced to a smaller scale, so that one line may contain three complete steps of a gallop. To make the sequence in beat intelligible, the impressions of the feet which strike the ground simultaneously are united by a diagonal and dotted line.

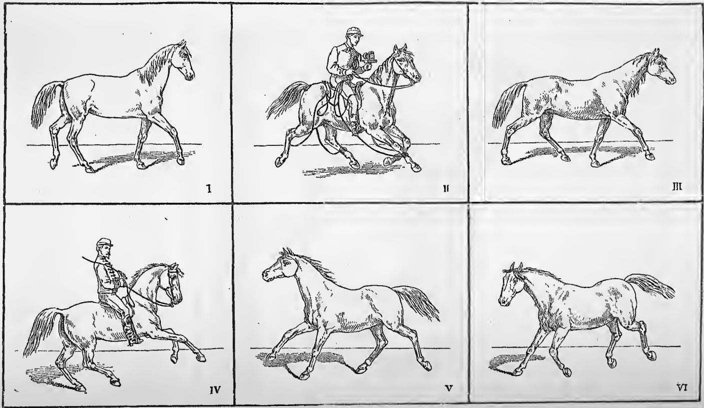

FIG. 130.—Table of the attitudes of a horse, designed by Col. Duhousset from chronographic charts.

as for horsemen. With the accurate knowledge afforded by chronography, which reveals the exact phases of rest or motion of each of the legs of a horse, combined with the knowledge afforded by the hoof-marks, we possess all the data necessary for constructing a perfectly accurate representation.

An artist familiar with equine paces could easily give a fairly correct attitude of an animal, but very often the representation deviates considerably from the reality. This is what has been proved by instantaneous photography of equine paces.

To prove satisfactorily that chronography combined with the measurement of the hoof-marks is not sufficient for the determination of the real attitudes of the horse, we will give an example in the form of

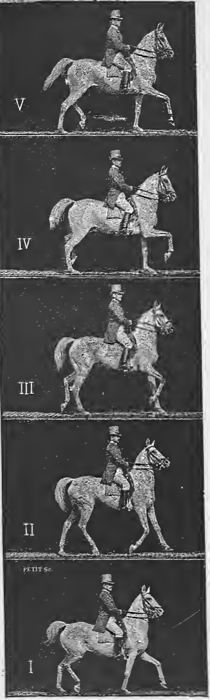

FIG. 131.—Horse walking.

two illustrations. Firstly (Fig. 130), the attitude as drawn from graphic analysis; * secondly (Fig. 132), the same as taken from photographs by Muybridge. This comparison is not to the advantage of the first diagram, in which it may be seen that the positions of the elevated feet are in some ways very unnatural. These discrepancies occur almost exclusively when an attempt is made to represent galloping, for in this pace the diagrams constructed from chronographic data alone are particularly at fault.

Chronography as applied to the Representation of the Horse in Motion.—Everybody is familiar with Muybridge's beautiful photographs, to which we have just alluded. They have furnished exact evidence concerning the movements of horses. Since instantaneous photography has become so universal, there have been published a considerable number of magnificent photographs, of which artists have made advantageous use; but the photographs taken in series are undoubtedly the most instructive, as far as the sequence of the movements is concerned.

Considerable advantage accrues from the application of our chronophotographic method to researches of this kind. More portable than other cameras, ours is easily carried about, whatever be the field of operations. It gives the shortest exposure, and therefore the clearest images. We have obtained on moving films some extremely long series, which the restricted size of this book does not permit us to reproduce *in toto*.

Fig. 131 shows a horse at a walking pace. The fragment here given only represents five consecutive images out of a total of twelve, which comprise one entire step, as measured from the moment the left hind

* These diagrams are taken from *La Machine Animale*. Paris, G. Baillière, 1873.

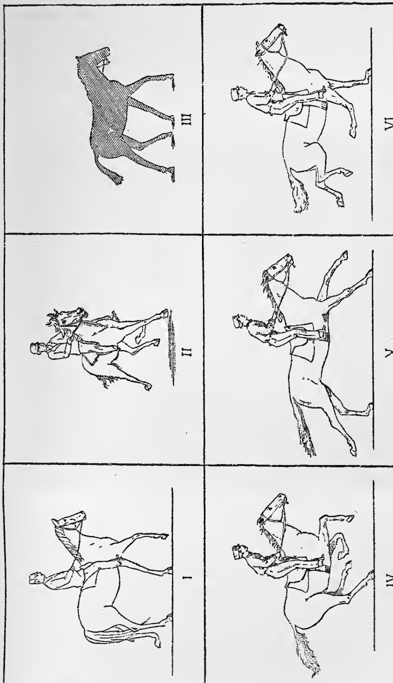

FIG. 132.—Table of the attitudes of a horse from instantaneous photographs by Muybridge.

foot reaches the ground till the same foot completes another step.

These images, when enlarged (Figs. 133 and 134), gain in clearness what they lose in detail. This is one of the disadvantages of this method of reproduction which is required in typography, but in impressions

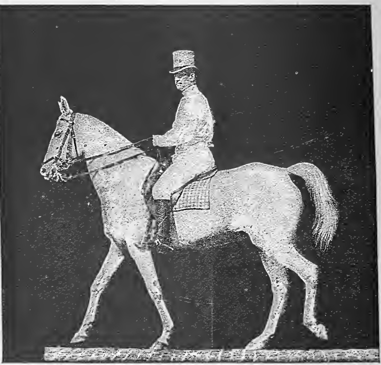

FIG. 133.—Horse walking (enlarged).

with thick ink the enlarged images still retain the detail.* Only three characteristic photographs of a galloping horse are represented in one series, and these correspond to the three beats of the movement, namely, the first, second, and third. The transitions and the changes of foot produce very elegant attitudes

* We propose, in *l' Atlas de Physiologie artistique*, to give a few series of photographs of the horse in its various paces.

(Figs. 136 and 137), among which, no doubt, artists will find some of which they can make good use.

The Uses of Photography in showing Marked Characteristics in the Forms of Animals.—In artistic representations, correctness of attitude is not all that is required. To this must be added correctness of form,

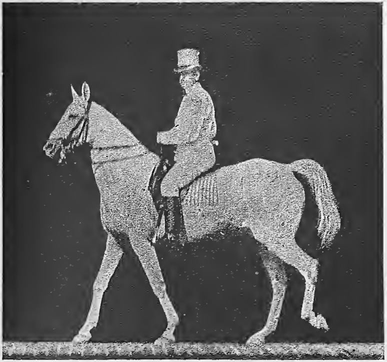

FIG. 134.—Horse walking (enlarged).

without which a movement cannot be successfully represented. Artists of remote antiquity appear to have acquired a knowledge of some of the paces, if not of the most complicated one, namely, that of walking. On looking at Figs. 138 and 139, examples of an ambling pace will be seen accurately represented.* It is of all

* These and most of the following figures have been borrowed from the Duhousset collection. They appeared in *La Nature*.

paces the easiest to observe on account of the

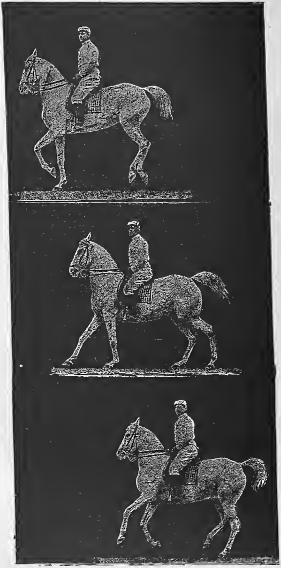

FIG. 135.—Horse at a canter. The series must be read from below upwards.

symmetry of movement; it is what is observed in the case of the ordinary gait of large animals, such as

camels and elephants; but beyond the accuracy with which the attitudes of the limbs are rendered, the execution otherwise is heavy, and the perfect synchronism of movement on the part of the two horses in the bas-relief of Medynet-Abou looks very ridiculous.

Yet more massive and unnatural is the horse represented at a walking pace in Fig. 140, but it shows that

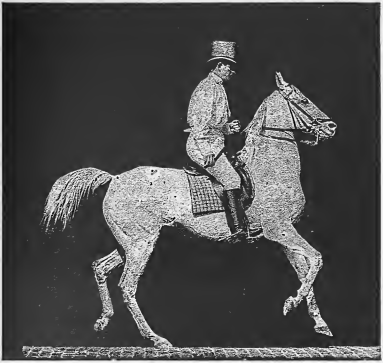

FIG. 136.—Transition from trot to gallop.

in Assyrian art there was even in those days a considerable knowledge of the movements of a horse, for the walk is, as we said, the most difficult pace to understand, and the one most often incorrectly drawn.

In ancient art, however, we sometimes meet with very correct ideas regarding this pace. First we have (Fig. 141) a bas-relief of the Volscian period; then two

figures on Trajan's column, a horse and rider (Fig. 142); and a pack-mule (Fig. 143).

Trotting, which is so often represented in modern works, seems rarely to figure in that of the ancients. Albert Durer sometimes gave an example of it, as

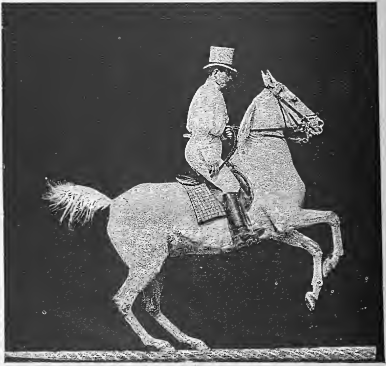

FIG. 137.—Changing step in a gallop.

shown in Fig. 144. Then there is the classical horse of Henry IV. on the Pont-Neuf (Fig. 145).

As for galloping, it is, perhaps, the most familiar pace in Greek art. The Parthenon frieze offers numerous examples of it. But there is little variety in the particular phase chosen by the school of Phidias to represent the movement. It is nearly always the first beat of the gallop which is represented, that is to

say, the moment when the horse is supported by one hind foot.

Fig. 146, taken from a fragment of the frieze still in

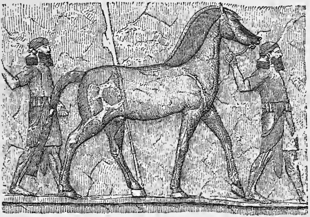

FIG. 138.—Assyrian bas-relief. Horse at an amble (British Museum).

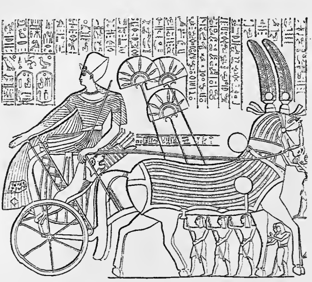

FIG. 139.—Egyptian bas-relief (Medynet-Abou). Two harnessed horses moving at an amble.

position at the Acropolis, represents an example of this kind. All these figures differ very much from the

rapid galloping we are accustomed to see represented in modern works. The Parthenon horses seem to make no advance, although they go through the

FIG. 140.—Assyrian bas-relief (Ninive) horse walking.

FIG. 141.—Bas-relief on burnt clay Volscian period (Velletri). Three harnessed horses walking.

movements of galloping; or, if they appear to move at all, at nothing more than a processional pace.

Locomotion of the Horse from the Physiological Point of View.—Art and Science join hands in searching after

Fig. 142.—Cavalier at walking pace (Trajan's column)

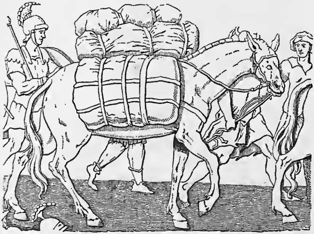

Fig. 143.—Mule walking (Trajan's column).

truth. The same methods serve equally well for

determining the various attitudes in which an artist

FIG. 144.—The Horse of Death, by Albert Durer. The horse is at a slow trot.

FIG. 145.—Statue of Henry IV. on the Pont-Neuf. Horse at a trot.

should represent a horse, and for following the phases

of its movements from a physiological or mechanical aspect. We have applied the method of geometrical chrono-photography to the study of equine paces, so as to obtain a large number of photographs on a fixed plate in series, and to show the movements of each of the segments of the limbs; in fact, just as we did in the case of human movements. It would be very difficult to cover a horse with black velvet, and to arrange on it black spots and lines marking the different joints and the various axes of the long bones. We, therefore,

FIG. 146.—Frieze at the Parthenon. Horse at a canter.

chose an animal with a dark coat, and in places we deepened the colour by painting it with lamp-black. Then, on the principal joints, we fixed little pieces of white paper, the shape being different for each joint—one square, another triangular, another straight, and another circular, and so on (Fig. 147). The animal was then made to pass in front of a dark screen, and a series of trajectories of the joints was thus obtained. In the enlarged photograph, the different joints had to be connected by lines, so as to indicate the positions of

the skeletal bones. This was a troublesome task, on account of the number of joints, and because the images of the hind-quarters were superimposed in those of the fore-quarters. With the assistance of Dr. Pagès, we have constructed diagrams of the movement of horses at different paces, although the individual trajectories of the various parts are occasionally rather complicated (Fig. 148).

In galloping, chronophotography demonstrates very

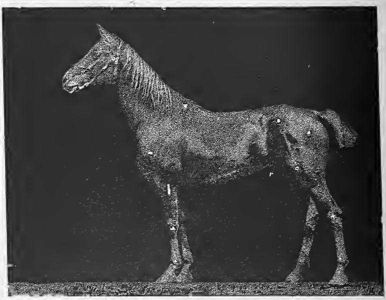

FIG. 147.—Horse prepared for experiments with geometrical chronophotographs.

strikingly the part played by the elastic flexor tendon in breaking the shock of the hind foot as it strikes the ground, for at this moment the foot supports the entire weight of the body.

One of our figures shows that the fetlock executes an alternating movement. The extent of this retrograde movement at the moment of contact is very considerable in long-limbed horses. This explains the easiness of their action. All this shows the advantages of

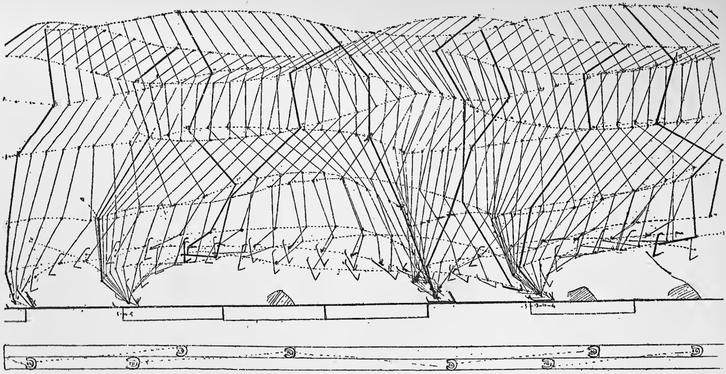

FIG. 148.—Diagram of the movements of the right anterior and posterior limbs of a horse at a walking pace.

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geometrical photographs for solving a number of technical questions relating to equitation. But it is a subject which in our eyes possesses a peculiar interest, for by it we learn how an animal's paces are affected by the shape of its limbs. This knowledge is absolutely necessary for the study of comparative anatomy, for it explains the real significance of the various shapes of the bones and muscles.

CHAPTER XII

LOCOMOTION IN WATER

SUMMARY.—Different types of locomotion in water—Method of photographing aquatic animals—Jelly fish: Comatulæ—Locomotion by means of undulatory and lateral movements; the eel—best arrangement for studying its movements—Locomotion by means of undulatory and vertical movements; the skate—special arrangement for studying its vertical undulations from different points of view—Undulatory movements of the skate as seen from the side: ditto as seen from in front—The sea-horse: the fresh-water tortoise—Slow movements of star-fish—Locomotion of small marine animals.

Different Types of Locomotion in Water.—Terrestrial animals make use of the ground as a fulcrum or fixed point of support, and their various kinds of locomotion depend on the following mechanism: A more or less sudden effort on the part of the limbs tends to repel the ground in one direction, and the body in the other. Now, since the ground offers almost absolute resistance, the whole effect of the muscular effort is expended on the body of the animal.

The locomotion of aquatic animals is quite different, with them the fulcrum, or point of support, is a displaceable liquid, and hence more or less of the muscular energy is expended on useless work.

The various kinds of propellers which men think they have invented for the purposes of navigation, such as sails, oars, and sculls, are represented in the highest degree of perfection in the locomotor organs of aquatic

animals. If the rotatory motion of the screw plays no part in organic nature, there are at least certain undulatory movements of the body or tail of certain animals, which, from a functional point of view, are entirely analogous to those of a screw.

In addition, aquatic animals have other means of propulsion, the like of which men have never made use of, and which might perhaps be tried with advantage.

Without attempting to offer a complete list of the various modes of progression represented among aquatic animals, the following may be enumerated.

Progression by the force of reaction—animals which project a stream of water: jelly-fish, octopuses, larvæ of certain insects, bivalve molluscs.

Progression by means of certain organs which meet with unequal resistance in the two phases of movement: comatulæ, crustaceans, etc.

Progression by means of an undulatory movement, propagated along the body in a direction opposed to that pursued by the animal: eels, long-bodied fish.

Progression by means of alternate shocks from a flexible paddle: aplysia, carinaria, and most fishes possessed of a caudal fin.

The possession of an aquarium facilitates the study of aquatic locomotion. But, as in the case of all other animal movements, the eye is frequently unable to follow manœuvres so rapid and complicated.

The following are the fruits of our first attempt to apply chronophotography to the elucidation of this subject, concerning which at present so little is known.

Method of taking Photographs of Aquatic Animals.—The methods vary very much according to circumstances. In the simplest cases, the object-glass is directed towards an aquarium provided with glass sides, and let into the outside wall of a room (Fig. 149).

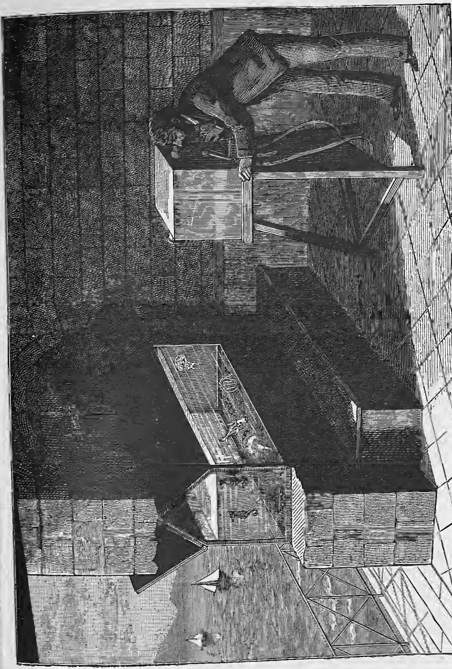


Fig. 149.—Arrangement of the marine aquarium for studying locomotion in water.

Sometimes a white cloth, set at an oblique angle, serves as a reflector and luminous background, against which the animals are silhouetted.

A series of photographs are taken on moving films, to show the successive attitudes corresponding to the phases of movement. The chief difficulty consists in compelling the animal to move in a limited space, so as not to leave the prescribed area of the photographic plate.

Four lines are traced on the walls of the aquarium, so as to form a rectangular space on which to focus. The observer then watches till the animal crosses this space, and although the transit may occupy only a fraction of a second, a series of from ten to twenty photographs can easily be taken in the time. This will be quite sufficient to show the phases of the movement.*

Jelly-fish are fairly easy to study, owing to the transparency of their tissues; and some of the details of their internal structure can be seen silhouetted in the photograph (Fig. 150).

By means of a rod introduced into the aquarium, a jelly-fish can be brought into the field of the object-glass. The alternate contractions and relaxations of its bell may be noticed, each of which operations displaces a certain amount of water, and, by means of the reactionary impulse, the animal is propelled in an opposite direction. If a jelly-fish takes up a vertical position, the direction of progression is from below upwards, and the animal rises in the water; if it is horizontally inclined, the direction of progression is in a corresponding direction.

The locomotion of a comatula is exceedingly curious. It is usually found fixed on some solid support like

* The size of the page being too small for such a long series, we can only give incomplete specimens of these photographs.

a flower by its stem, and there it executes movements which are so slow that they almost escape observation. But if separated from its attachment, and irritated by means of a rod, it soon begins to throw its arms about in a rapid manner—movements which result in its removal from the unwelcome object. As in the case of the jelly-fish, the direction of movement corresponds to the long axis of the body; by inclining its cup

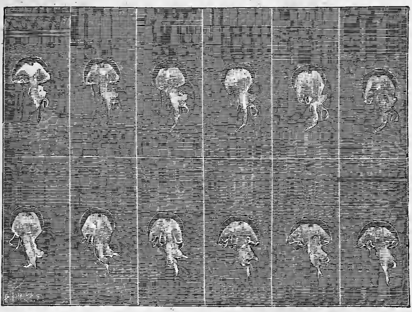


FIG. 150.—Movements of the bell of a medusa. The first position is the first of the upper series on the right; the last position is the one on the extreme left of the lower series.

obliquely, it can alter the direction of progress. In the case here represented (Fig. 151), the animal was trying to rise from the bottom of the aquarium.

The following is the method of propulsion. The arms of a comatula are ten in number, five invariably move upwards, and five downwards; two neighbouring arms never move in the same direction. Those which rise upwards approach the axis of the body,

those which descend recede from it. Sometimes in the phase of upward movement, the fine processes on the arm can be seen flattened down against it by the resistance of the water. In the phase of downward movement, the same processes are separated out, become visible, and meet with resistance from the water, which thus acts, as it were, as a fulcrum to assist the animal in its locomotion.

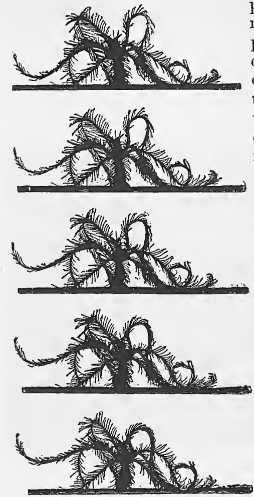


Fig. 151.—Comatula executing movements at the bottom of the aquarium. The series must be read from below upwards.

Locomotion by means of Undulatory and Lateral Movements: Eels.—Eels, and fishes of a similar shape, progress in a horizontal direction by means of an undulatory motion of their bodies. To observe this movement satisfactorily, the observer should place himself above the animal: a special kind of aquarium is required for taking chronophotographs.

Special Arrangement for Studying this Movement.— The light should come from below; in fact, the arrangement shown in Fig. 51, Chap. V., answers very well for these researches. The eel is silhouetted against the luminous background, and the object-glass of the apparatus is directed vertically downwards, or else a silvered mirror, inclined obliquely at an angle of 45°, reflects the image of the fish towards the object-glass, which is then set horizontally.

Fig. 152 represents a series of photographs in which the progression of the animal can be followed, as well

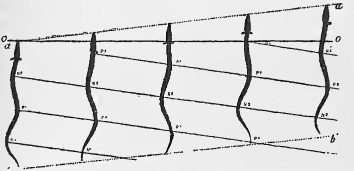


FIG. 152.—Eel moving in a horizontal plane. The horizontal line *oo* enables the reader to appreciate the degree of obliquity of the lines which join the ventral and nodal portions of the curves into which the body is thrown. The degree of velocity of progression is expressed by the obliquity of the line *aa*.

as the undulatory movements along its body. The oblique lines indicate the propagation of these waves in relation to the horizontal line *oo* with which the head of the animal would be on a level in the entire series were it not for the progress made. The line *aa*, obliquely inclined, shows in each instance how far the eel has advanced. This line is straight, and consequently proves that the velocity is uniform. In the fifth image, *i.e.* at the end of half a second, the eel has advanced a distance equal to a quarter of its own length, say about 0·075 metres, which corresponds to a rate of 0·15 metres per second. Further, the

lines $p^1, p^2 \ldots n^1, n^2 \ldots$, which unite the ventral and nodal portions of the same wave, express, by their degree of obliquity with respect to *oo*, the velocity of each.

Actual measurement shows that the velocity of the waves is greater than the rate of progress of the animal, and that they travel in an opposite direction. There must be, therefore, a recoil, as in the case of the screw of a steamer, and it is due to the mobility of the resisting-point.

Thus, the direction of movement of these undulations in an eel, as it moves forward, are directed from the head towards the tail. We believe that these fish, when they want to move backwards, reverse the direction of these undulatory movements, namely, that the wave travels from the tail towards the head. But this phenomenon is difficult to produce, and we have not yet been able to prove it by chronophotography. We studied in the same way the locomotion of various kinds of snakes, both terrestrial and aquatic; the crawling of the former and the swimming of the latter are very similar to the movement of an eel, but we could not observe the same regularity of motion.

Locomotion by means of Vertical and Undulatory Movements: the Skate.—The skate, like an eel, progresses by means of undulatory movements, but the wave is produced symmetrically by the animal's two fins. The movement is in a vertical direction. To photograph this movement the animal must be viewed from the side; an aquarium, as before described, is suitable for this purpose. The difficulty which arises in this experiment is that of keeping the fish in a convenient position, so as to show its movements clearly. Left to itself in an aquarium, the skate remains motionless at the bottom; yet if disturbed it swims to the surface, and causes a disturbance of the water by flapping its fins, and it is but seldom that it swims

quietly in a forward direction. To keep a skate within the field of the object-glass, and to make it execute its proper movements of natation, we finally, after various attempts, settled on a method which answered admirably.

Special Arrangement for studying the Vertical Undulations from Different Points of View.—Fig. 153 shows an apparatus for holding the animal. A flat strip of iron has its two ends bent at right angles; holes are bored in corresponding positions in the two uprights, and two iron wires are passed through them, and tightly stretched. On these two wires two glass tubes

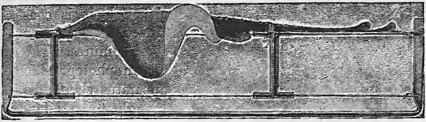


Fig. 153.—The skate. Method of fixing the animal when observing the movements of its fins.

are threaded, and united by cross-bars. The latter are provided with clips for holding the fish. One of the tubes is fitted with a toothed forceps for holding the front part of the fish; the other is provided with a plate on which the tail end rests, and to which it is fastened by means of a ligature.

The fish is then held immovable between these two points of attachment; the latter are more or less widely separated, according to the length of the fish. The iron plate rests at the bottom of the aquarium, and the object-glass is focussed on the fish.

The skate thus held in position can neither advance nor recede, but it can use its lateral fins as much as it chooses; nevertheless, it seldom takes advantage of

this liberty, and only moves them when irritated. We have found the most successful way of doing this is to scratch it beneath the tail with a piece of stick. A curious result follows: an undulatory movement of the fins is propagated down the length of the body, taking a direction from the head to the tail. The movement can hardly be seen with the eye, although it is continued perhaps for some minutes. The chronophotographic apparatus should be brought to bear during such a period of movement.

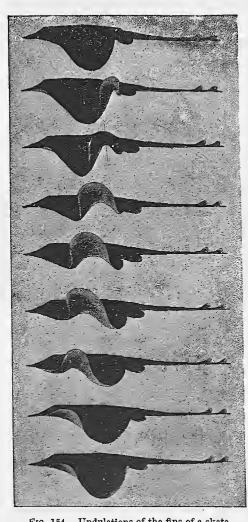


FIG. 154.—Undulations of the fins of a skate, viewed from the side.

Undulatory Movements of the Skate as seen from the Side.—When the fish is viewed from the side, a series of photographs may be obtained such as appears in Fig. 154. The undulatory movements commence at the anterior end of each fin, and are propagated in a posterior direction, increasing in amplitude as they proceed. As fresh portions of the fins are raised, those behind are lowered, so that the centre of the wave,

namely, the most elevated part, travels rapidly from the head towards the tail. Having run its course, the wave elevates the posterior extremity of the fin, and then disappears. But another wave is already commencing at the anterior end, growing larger, and travelling along in the same way as the one which preceded it, and so on *ad infinitum*.

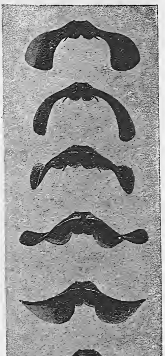


FIG. 155.—Undulations of the fins of a skate, viewed from in front.

It would be interesting to observe what disturbances are caused in the water by these undulatory movements. This could be ascertained, we think, by introducing into the aquarium some of those little bright beads which served to show all the movements in liquids mentioned in Chapter VI. We by no means despair of obtaining photographs of a skate swimming in the normal free state—it is only a matter of time and patience.

Undulatory Movements of the Skate as seen from the Front.—With the express object of studying the movement of the fins from another point of view, we fixed the animal in a new position, by giving half a turn to the iron framework.

In this new arrangement the axis of the fish ran in an antero-posterior direction, the head facing the photographic apparatus. The series of photographs

(Fig. 155) shows how the skate raises and lowers the flexible edges of its fins, or, rather, how the resistance of the water elevates them when the base of the fin is lowered. When we come, later on, to demonstrate the appearance of a bird's wing as it strikes the air the same appearance will be noticed. In fact, the two movements have the same effect, both propel a fluid by an oblique movement of an inclined plane.

The undulatory movements of the skate which we have just described, and which are apparently due to the co-ordinated action of successive portions of the

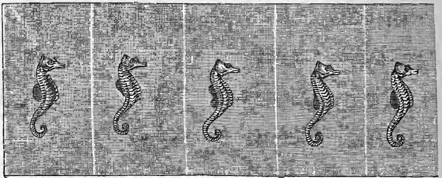


FIG. 156.—Sea-horse, showing the successive and ascending phases of the undnlations of the dorsal fin as the animal descends through the water.

fins, is similarly to be found in other aquatic species. Cuttle-fish move their lateral fins with a very similar motion, as far as one can judge by simple observation, for we have not yet had an opportunity of photographing the movements of these molluscs. It is a remarkable fact that cuttle-fish can alter at will the direction in which the movements of their fins are propagated. They can be seen swimming in an aquarium either to the right or to the left without turning round. If they advance, the undulating movement of their fin passes from the head-end towards the tail; if they go backwards, the wave passes in the contrary direction. It must, however, be understood that

this alteration in the direction is entirely independent of the action of the siphon. Even in molluscs of too humble an organization for such co-ordinated movements progression by means of a wave-like movement may be observed.

Fresh-water tortoises swim in various ways; generally their mode of progression is something like that of quadrupeds; that is to say, with diagonally associated movements of the limbs, noticeable, for instance, in trotting.

In exclusively marine species, the feet are shaped something like fins, or, rather, like wings, and the movement of the anterior appendages is much like that of a bird. The result is a kind of flight through the water, something similar to that of a penguin. This kind of locomotion, which we have as yet had no opportunity of studying by means of chronophotography, is a functional link between chelonians and birds—animals which are closely allied in morphological characteristics.

Slow Movements of Star-fish.—The slow movements of certain aquatic animals are easily studied by means of a series of photographs, and they form an interesting subject of investigation. Nothing is more fascinating than to watch the evolutions of a star-fish, which has turned on to its back, in its attempts to regain its normal position. It finally succeeds by extraordinary feats of equilibration. It can be seen (Fig. 157) gradually insinuating one of its rays beneath its body, while it raises two others until its centre of gravity is outside the base of support. Then, all of a sudden losing its balance, it falls forwards on to its ventral surface. There is now nothing left to be done except to extend its rays and gradually assume its normal position. It then moves along the bottom of the aquarium with a crawling motion peculiar to star-fish.

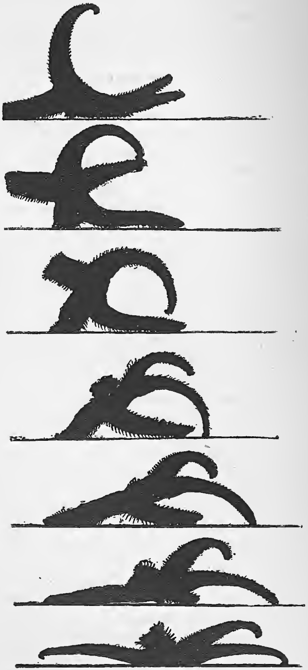


FIG. 157.—Phases of the movements of a star-fish in turning itself over. Series of images to be read from below upwards.

This somersault takes some time to accomplish, usually ten to twenty minutes; therefore at least an interval of one minute should be allowed between two successive photographs if the various phases are to be clearly depicted.

Locomotion of Small Marine Animals.—If the movements are small, and if they have to be studied at a near distance, a special arrangement must be adopted. Two cover glasses should be cemented together, and a small aquarium made just about the same size as

FIG. 158.—Movement of the appendages of a shrimp.

the field of the intended photograph. The case is then filled with sea-water, and the animal—a shrimp, for instance—introduced; by taking on a moving film successive photographs, which are silhouetted against a luminous background, a series of pictures representing the movements of the appendages is obtained.

Further on, a similar arrangement for the study of the flight of insects will be described. Finally, these small animals can be studied under a microscope by an arrangement presently to be described.

CHAPTER XIII

AERIAL LOCOMOTION

The Flight of Birds

Summary.—Borelli's theory on the mechanism of the flight of birds—Chronography used for determining the frequency of the movements of the wing, and the relative duration of the rise and fall—Myography—Method of recording the phases of contraction and relaxation of the wing muscles—Record of the trajectory of a bird's humerus, and the variations in inclination of the surface of the wing—Photographic trajectory of the tip of the wing—Chronophotography as showing the successive attitudes of the bird during the different phases of movement of the wings—Photographs of birds taken from different aspects—Simultaneous chronophotography.

Of all kinds of locomotion, as existing among vertebrates, that of birds has remained the longest unexplained. In a rather obscure passage, Borelli compares the wing action to that of a wedge; meaning by that expression that the surface of the wing bears an oblique relationship to the direction of movement, and that the resistance of the air can be resolved into two separate forces, one of which sustains the weight of the bird, while the other urges it in a forward direction. This interpretation is legitimate in view of the analogy correctly established by Borelli between the propelling action of the wing and that of a fish's tail.

Being ourselves extremely interested in the mechanical problem of flight, we have for several years

past occupied ourselves in determining the nature of the wing movements, and to this end we have adapted every possible means of mechanical appliance. These experiments furnished us with important information regarding the frequency of movement, and the reasons for variation. We also obtained records of the muscular contractions which occurred in flight, and their variations among different species of birds. Even the trajectory of the point of the wing, and the inclination of the wing-surface during the different phases of movement, have been determined by this method. It is, however, chiefly by means of chronophotography that the complicated actions involved in the flight of birds has been fully explained.

As we have fully described these experiments elsewhere,* we need only refer briefly to the two methods which have thrown new light upon this subject.

Employment of Chronophotography in determining the Duration of the Rise and Fall of the Wings.—As in the case of terrestrial locomotion, it is by mechanical means that the frequency of a bird's movements, and the phases of muscular activity which result in flight, can be best ascertained.

Chronography and myography have both been successfully used in these determinations. To measure the frequency of the wing movements an electric chronograph was employed to register on a revolving cylinder the make and break of an electric current, the interruption being brought about directly by the movements of the wing. For this purpose the bird had a small flexible plate fixed to the extremity of one of its remiges, which was bent in different directions by the resistance of the air as the wing was raised or lowered. A double and very flexible wire connected the bird with the chronograph and battery,

* *Le Vol des Oiseaux.* Paris, Masson, 1890.

so that the bird could fly freely about in a large room. The descent of the wing closed the current, and during its ascent the current was broken, so that each flap of the wing left a mark on the cylinder, just such as that caused by the rise and fall of a man's foot in walking.

By counting on the tracing the number of ascents and descents executed by the wing in a given time, the frequency of wing movement proper to each species could be obtained with the greatest exactness.

It will be noticed that, following the general laws applicable to living beings, the smallest birds have the most rapid movements; the sparrow giving twelve strokes to the second, the pigeon eight, and the buzzard three. The relative duration of the rise and fall of the wing can be measured by means of the same chronographic tracing. These two phases are of unequal duration, especially in the case of large-winged birds, the duration of descent being considerably longer than the period of ascent. This is entirely contradictory to all preconceived notions.*

Registration of Muscular Actions.—Mechanical registration is the only means we have at present for determining the phases of contraction and relaxation of the wing muscles. A pigeon (Fig. 159) is provided with a closely fitting corset, under which is slipped a "myographic capsule," which is arranged so as to

* "By means of this method we have been enabled to demonstrate experimentally one of the most important points in the mechanism of flight, namely, that the wing meets with greater resistance from the air the more rapid the progression of the bird. It appears that if a bird is travelling at a certain rate it continually comes in contact with fresh resistance from the air, and it is the inertia of these new masses of air which has constantly to be overcome. On the other hand, if the bird is stationary when it takes a stroke with its wings, the air which is struck disappears from under the wing and offers no more resistance. Hence it is that if a bird intends to take flight, it first tries to acquire a certain velocity, either by taking a run, or by dropping a certain distance from an elevated position."—*Le Vol des Oiseaux*, p. 249.

record the contractions of the pectoral muscles. A long flexible tube unites the capsule and the chamber of a recording tambour. This tube does not impede the bird's flight, but allows a record to be obtained which shows variations according to the species of bird used in the experiment. By means of a tuning-fork and chronograph, the duration of the different phases of muscular action occurring during the movements of the wings can be estimated to $\frac{1}{100}$ of a second.

We will not dwell upon the interpretation of these curves, since the variations depend largely on questions of comparative anatomy.

Record of the Trajectory of a Bird's Humerus.—To fully understand the mechanism of the wing movement, we set up some rather complicated apparatus so as to register the trajectory of the humerus of the bird with the variations in inclination of the surface of the wing at different periods of the movement. In different species we found the form of the curves slightly different, but they all took more or less the shape of an ellipse, the principal axis of which was directed downwards and forwards. These experiments were very difficult to carry out; we succeeded, nevertheless, in repeating them a number of times with practically the same result, and the buzzard which we used in the experiments in the end became quite tame and accustomed to the apparatus.

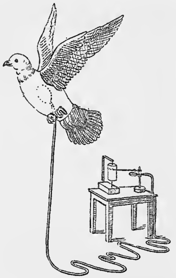


FIG. 159.—Myographic record of the pectoral muscles of a bird in flight.

The trajectory of the humerus of the buzzard proved

that this bone described round the shoulder joint a cone with an elliptical base, and that the posterior edge of the wing was raised as the wing was depressed. This was due to the resistance of the air. After the phase of depression was over, the feathers, by reason of their resiliency, returned to their natural position,

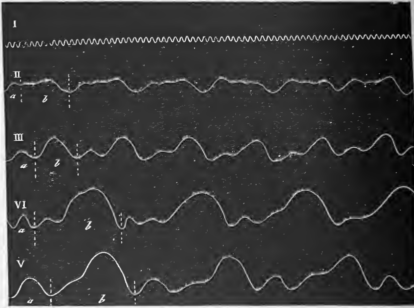


FIG. 160.—Myographic curves taken from different birds in flight. Line I, chronographic curve 100 vibrations to the second. Line II, tracing of a pigeon's muscle. Line III, duck's muscle. Line IV, buzzard's muscle. Line V, hawk's muscle. In all the tracing the undulations *a* correspond to the elevation of the wing, and the undulations *b* to the descent.

so that during the period of the rise the under surface of the wing was turned slightly forwards.

Chronophotography applied to the Study of Flight.—It might be urged that the apparatus which was fitted to the bird could modify the character of its flight. So no sooner had we devised the chronophotographic method than we made use of it to control the results obtained by purely mechanical means. The results

Fig. 161.—Chronophotographic illustration of a gull during flight.

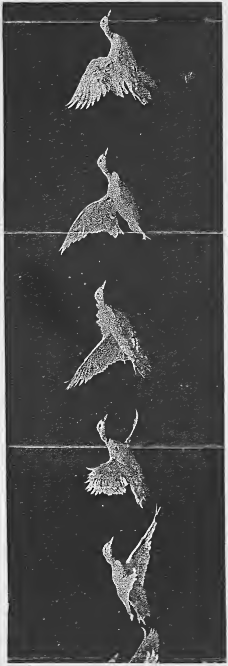


Fig. 162.—Flight of a duck. The vertical lines, which are one metre apart, enable one to estimate the rapidity of flight. In reading from right to left the wing becomes successively lower. The series must be read backwards (10 images to the second).

were not only fully confirmed, but this new method also completely explained the movements of flight.

In this research, as in those on different kinds of locomotion, it was necessary to combine several methods, each with its own particular object. Direct registration, with its continuity of record, was always made use of when it was necessary to determine the frequency and duration of a given movement of a part of the body. Chronophotography was useful when a general idea of the movement was desired; it was also the only means by which the movements of an isolated point could be expressed, when the movement was not accompanied by the development of a certain amount of force. An example of this kind may be seen in the trajectory described by the extremity of a wing. It is impossible to apply a registering apparatus to the end of a flexible feather; but the true interest of chronophotography lies in the fact that it can provide a complete picture of a bird in the various attitudes it assumes during the act of taking a stroke with its wings.

Successive Photographs of Birds taken on the Wing.— If a white bird, brightly illuminated by the sun, is photographed in series as it crosses in front of a dark background, its various attitudes will be clearly seen. In these photographs the bending of the wings due to the resistance of the air is usually quite evident, and it expresses in a striking manner the force with which the wing is moved; if one tries to reproduce the same degree of bending by mere manual force one is quite astonished at the amount necessary. This curving of the feathers may be observed in all kinds of birds, but in different degrees according to the flexibility of the wings; thus, for instance, it is very pronounced in the case of a flying heron, just when the wing reaches the mid phase of descent (Fig. 163).

FIG. 163.—Flight of a heron. A metre scale in the lower part of the illustration makes it possible to estimate the rapidity of flight.

Photographs of Birds taken from Different Aspects.—If one is dealing with a movement which is quite invisible to the unaided eye, a single series of photographs taken only from one point of view is usually quite insufficient; it does not give an accurate idea of the movement at any particular moment. Therefore, it is desirable to take photographs from one or two different angles. For instance, one photograph should be taken as the bird is flying towards the camera; another as it flies across it; and a third should be taken from above, with the camera looking down-

FIG. 164.—Flight of a pigeon. The photograph is taken from above (chronophotograph on a fixed plate, 25 images to the second).

wards. Fig. 164 shows a photograph of a pigeon taken from above. The camera was directed vertically downwards at a distance of 12 metres from the bird. In spite of the confusion resulting from so many images (25 to the second), the curious positions of the wings at different moments are clearly shown. The various positions can easily be distinguished after a little practice in interpreting the meaning of this kind of photography.

Chronophotography on Moving Films.—To take a large number of images per second without confusion,

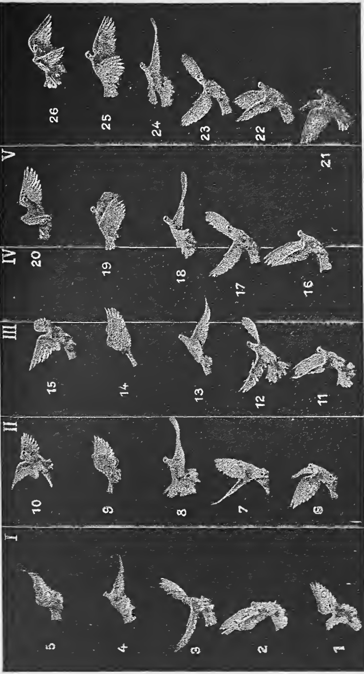


FIG. 165.—From a photograph of a pigeon taken in front of a dark background. A moving film was employed with 60 exposures in the second.

recourse must be had to chronophotography on moving films. By making use of a dark background we have obtained as many as 60 distinct images per second. Fig. 165 is an example of this kind; the film is cut into six pieces, which are placed side by side in the illustration. The images are numbered in ordinary figures, according to the order in which they were taken.

Simultaneous Photographs of the Same Bird taken

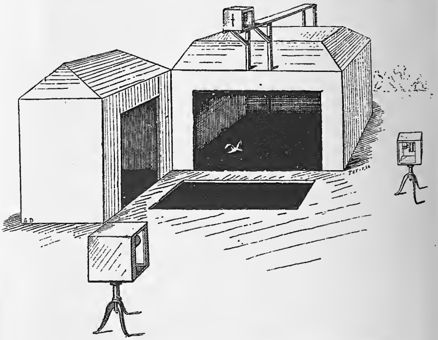


FIG. 166.—Arrangement of the three dark backgrounds and the three cameras for simultaneous photography of a flying bird, as seen from three points of view.

from Different Aspects.—If we want to analyze the movements of flight with extreme exactness, the bird must be photographed from several points of view. Three cameras are usually required for this purpose, as well as three dark screens against which the object is clearly visible. The arrangement is represented in Fig. 166.

By this means we were able to obtain the attitudes of the bird in three series: from the front, from the

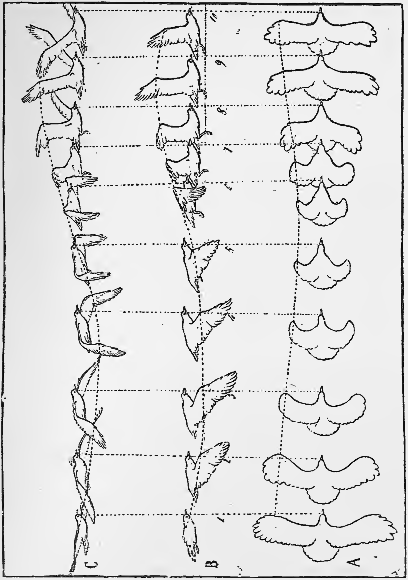


FIG. 167.—Three series of images to demonstrate the corresponding positions of the bird, when taken from three different points of view. A, taken from above; B, from the side; C, obliquely from the side and front.

side, and from above. The three sets of photogarphs

were made to correspond to the same attitudes * for convenience of comparison, and to show the exact position in space of the body and wings (Fig. 167).

From these photographs we have been able to construct a series of bas-reliefs showing the successive attitudes of the bird.

This kind of representation is almost the only way of illustrating the actual movement during flight, for mere ocular observation would not give the least idea.

* "We need not here repeat the analysis of these photographs, which have afforded us complete information of the movements of birds from the point of view of kinetics, and from which we have attempted to measure the amount of work performed during the act of flying by means of the degree of acceleration imparted to the body."—See *Le Vol des Oiseaux*, p. 324.

CHAPTER XIV

AERIAL LOCOMOTION

The Flight of Insects

Summary.—Frequency of the movements of insects' wings as estimated by the sound produced in flying—Mechanical registration of the movements of the wings; frequency among different species—Synchronous movements of the wings—Changes in inclination of the wing surface—Trajectory of an insect's wing—Its interpretation—Experiments to demonstrate the direction of movement of the wing, and its variations in plane—The artificial insect—Theory of the flight of insects—Photography as applied to the study of insect flight—Lendenfeld's experiments—Trajectory of the wing as the insect advances—Photography on moving films—Arrangement of the experiment—Different types of flying insects: Bees, flies, tipulæ—Substantiation of the mechanical theory of flight.

Frequency of the Movements of Insects' Wings as estimated by the Sound produced in Flying.—The flight of insects is accompanied by a humming sound, which is of somewhat low pitch in the larger species, and of very high pitch in some of the smaller insects, such as mosquitoes. The wings of insects may be regarded simply as vibrating wires, and hence the frequency of their movements can be calculated by the note produced. But then it must be taken for granted that the four wings of an hymenopterous, or the two wings of a dipterous insect vibrate in perfect unison. In calculating the frequency of the movement of the wings by this method, the following difficulty may be met with. If we listen to a fly on the wing, it will be

noticed that the character of the sound continually changes. By close attention, the sound can be distinguished as of a higher pitch when the fly approaches the observer, and of lower pitch as it recedes. This suggests that there must be an alteration in the frequency of the wing vibrations. The phenomenon may, however, fairly be compared to the apparent variations in shrillness of the whistle of a moving train. As the train rushes along, the whistle seems to become shriller when it approaches, and deeper when it recedes. This acoustic phenomenon has long ago been explained. However, if we hold an insect lightly in a

FIG. 168.—The two top lines are produced by the contacts of a drone's wing on a smoked cylinder. In the middle are recorded the vibrations of a tuning-fork (250 vibrations per second) for comparison with the frequency of the wing movements. Below are seen the movements of the wing of a bee.

pair of forceps it may be shown that when its wings vibrate the sound produced is practically uniform.

Mechanical Registration of the Movements of Wings in Insects.—The movements of the wings of a captive insect may be recorded directly on a revolving cylinder. If the cylinder previously be blackened with smoke the slightest touch will remove the black and expose the white paper beneath. Fig. 168 was obtained in this way, and shows several interrupted lines traced by the wing of a drone. The tracing was obtained as follows: The insect was held between a pair of forceps in such a way that the extremity of its wing only just came in contact with the surface of the cylinder, and in so

doing left an interrupted track. If the wing had been forced harder against the cylinder, the mark left would have been somewhat in the form of a comma, and the frequency naturally somewhat less owing to the resistance due to friction. The same effect may be observed in the movements of all kinds of animals.

To calculate exactly the frequency of the wing movements, the vibrations of a tuning-fork are simultaneously recorded on the cylinder. These vibrations leave on the blackened paper an undulating line; each vibration representing $\frac{1}{250}$ of a second. It now only remains to count the number of marks traced by the insect's wing on a length of paper corresponding to 250 vibrations of the tuning-fork. The number of wing movements per second is thus obtained.

By this method it was calculated that in the common fly there were 330 strokes per second, in the bee 190, and in the macroglossus of cheese rennet 72. Thus obeying the general law applicable to birds, namely, the smaller the species the more rapid the movements of the wings.

Synchronous Movements of the Wings, Variations in Surface Inclination.—There are other facts to be learnt from direct registration of the wing movements. Thus by holding a fly in such a position that its two wings strike the cylinder at the same time, it will be seen that both wings impart the same number of strokes, and that the movements are absolutely synchronous.

In some species of insects the upper surface of the wings is covered with fluffy hairs, while the lower surface is bare; tracings taken from the wings of such insects show alternate variations. Fig. 169 was obtained from Macroglossus of cheese rennet, a small diurnal hawk moth which flies very rapidly and is very common in France. The insect was held in such a way that the under side of its wing touched the cylinder.

Now, in moving to and fro, the wing struck the cylinder alternately with the hairy and smooth surface, which proved that the wing underwent a change in inclination. This fact is important to bear in mind, for it materially elucidates the mechanism of flight. Such is the information derived from recording insect movement by means of mechanical methods.

The attempt might be made to obtain the trajectory of the extremity of the wing by a similar means.

But the wing, moving as it does in all sorts of directions round its thoracic articulation, describes a spherical figure, the whole of which could not possibly

FIG. 169.—Movements of the wing of Macroglossus of cheese rennet on the surface of a smoked cylinder.

be traced on anything else than the inner surface of a sphere. The contact of the wing with the surface of the cylinder could only take place to a very small extent. Consequently another method must be employed for obtaining the trajectory described in the air by the extremity of the wing.

Trajectory of the Extremity of the Wing.—Remembering the fiery tracks left upon the retina when a luminous object was waved in front of the eyes, we fastened a spangle of gold-leaf to the extremity of a wasp's wing. The insect was then seized with a pair of forceps and held in the sun in front of a dark background. We then watched the luminous trajectory

which shaped itself in the form of a lemniscate, Fig. 170. The figure 8 would exactly express what we saw, and the resemblance was the more complete because, in the trajectory thus described, one of the limbs seemed

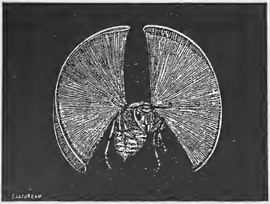


FIG. 170.—Appearance of a wasp flying in the sun. The extremity of the wing is gilded.

larger and brighter than the other. In describing this appearance we ignored, or omitted to mention the fact, that Mr. Pettigrew, in England, had noticed the same appearance in a flying insect, which gave rise on his part to claims of priority of discovery. Nevertheless, we may remark that the method of formation of the figure described by the wing of an insect, according to Mr. Pettigrew, is quite different from our conception. According to the English authority, the anterior border of the wing describes one limb of the lemniscate while the inferior border describes the other. In Fig. 171, which is borrowed from his work, the arrows indicate a complete reversal of the wing surface in a simple movement from left to right.

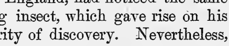


FIG. 171.—The trajectory of the anterior and posterior border of the wing of an insect during half an oscillation (Pettigrew).

According to our view, on the contrary, the extremity of the wing describes each limb of the lemniscate in succession, in a dual motion from left to right, and then from right to left. Meanwhile the surface of the wing is variously distorted by the resistance of the air. In Fig. 172 dotted lines indicate the direction of this distortion which could never amount to a complete reversal. Now, the mechanical theory which can be deduced from this optical figure depends entirely on the manner in which the wing is supposed to have described it. According to Mr. Pettigrew's theory, the revolution of the wing is active and due to the contraction of muscles. According to our theory, the change in inclination of the wing is passive and brought about by the resistance of the air, for it is only the posterior part of the wing that is distorted, the anterior part being kept straight and stiff by a rigid nervure. The importance of a correct interpretation of the figure described by an insect's wing is very great, because the explanation of the mechanism of flight depends upon it. We have, however, no desire to weigh the respective merits of the two theories, we only wish to enumerate the experiments by which we have demonstrated our own views.

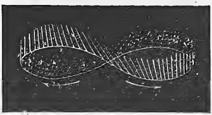


FIG. 172.—Trajectory of the anterior order of the wing during a complete oscillation (Marey). The small lines which are set obliquely in various directions represent the inclinations of the surface of the wing.

Experiments for determining the Direction taken by the Wing in course of Movement, and Explanation of the Mechanism by which the Alteration in Inclination is effected.—The optical method, namely, that of determining the movements of the wing by the impression left on our organs of sight by the gold spangle fastened

on the extremity of the wing, shows that the surface of the wing is differently inclined during the various phases of movement. Now, we have seen that the two limbs of the 8 described in this way are unequally luminous, and from this we concluded that while one of the limbs was being described, the inclination of wing must have been more favourable for the reflection of the sun by the gold spangle, and that, while the other limb was being described, the gold spangle must have had a less favourable inclination. If this is so, by altering the position of the insect, a change should be effected in the degree of reflection, and as a matter of fact this is exactly what does happen. When the

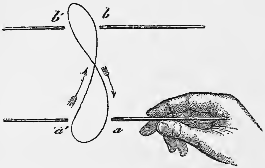


FIG. 173.—Experiment to test the direction of movement of an insect's wing.

insect is turned through an angle of about 90°, what was before the bright limb of the 8 is now no longer conspicuous, whereas the other side, in its turn, becomes brilliantly illuminated. In this way the variations in inclination can be demonstrated. Even the angle formed by the wing with the axis of progression could be deduced from these experiments, but we shall see that, by the employment of photography, this angle varies from moment to moment. The most that one can say is that the angle is about 45°, sometimes in one direction sometimes in the other.

To determine with accuracy the direction taken by

the wing at different stages of the trajectory, we proceeded as follows. A small piece of capillary glass tubing was blackened in the smoke of a candle, so that the slightest touch on the glass was sufficient to remove the black coating and show the direction of movement in each limb of the lemniscate. This experiment was arranged as shown in the figure (173). Different points on the path of movement were tested by the smoked rod, and from the track along which the black had been removed the direction of movement was deduced. This direction is represented in the figure by means of arrows.

For the sake of comparison, we constructed an artificial insect, the wing of which consisted, as in nature, of a rigid nervure anteriorly, and a sort of flexible sail behind. We have watched this little contrivance move like a real insect, give like it a luminous trajectory shaped like a lemniscate, agitate the air behind, and by a kind of suction action aspirate air towards it in front.*

Theory of Insect Flight.—The theory of insect flight may be completely explained from the preceding experiments. The wing, in its to-and-fro movements, is bent in various directions by the resistance of the air. Its action is always that of an inclined plane, striking against a fluid, and utilizing that part of the resistance which is favourable to its onward progression.

This mechanism is the same as that of a waterman's scull,† which, as it moves backwards and forwards, is obliquely inclined in opposite directions, each time communicating an impulse to the boat.

There is, however, a difference between these two

* *La Machine Animale*, book iii., chap. ii.

† This refers to what is generally called "sea-sculling," and of course has no reference to the ordinary river sculling, which requires the use of two sculls.—TRANSLATOR.

methods of propulsion. The scull used by the waterman offers a rigid surface to the water, and the operator has to impart alternate rotary movements to the scull by his hand—at the same time taking care that the scull strikes the water at a favourable slant. The mechanism in the case of the insect's wing is far simpler, the flexible membrane which constitutes the anterior part of the wing presents a rigid border, which enables the wing to incline itself at the most favourable angle.

The muscles only maintain the to-and-fro movement, the resistance of the air does the rest, namely, effects those changes in surface obliquity which determine the formation of an 8-shaped trajectory by the extremity of the wing.

Photography as applied to the Study of Insect Flight.—The reader may, perhaps, be surprised that we have not, as yet, resorted to photography as a means of determining the trajectory of an insect's wing, since this is the only method of recording an accurate tracing. This is because the experiments just mentioned were carried out long before photography could be employed to study any kind of movement. Photography was applied by Lendenfeld * for determining the position of the wings of a dragon-fly.

This author also showed how the lemniscate described by the extremity of the wing became displaced and distorted by the animal's forward progression. The experiments of the German naturalist were made on a dragon-fly, which was fixed at the end of a sort of balanced beam; and although the animal could raise itself to a slight degree, the conditions were not such as to indicate the normal trajectory of the wing, when the insect was free to fly where it liked.

* Lendenfeld, *Der Flug der Libellen*, Acad. der Wissenschaften. Vienna, 1881, Heft. i. p. 289.

We succeeded in obtaining a photograph of the gilded wing of an insect, which, though not absolutely at liberty, could fly at a comparatively high rate of speed.

Photography of the Trajectory of the Wing.—The following is the arrangement we adopted for our experiments. A wooden box one metre square and 0·25

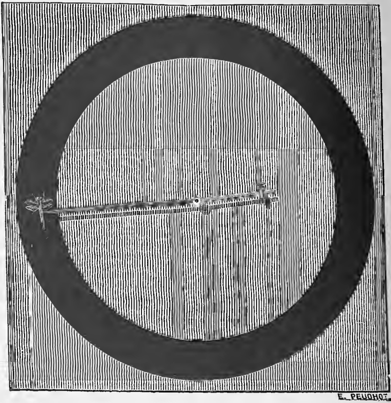


FIG. 174.—Insect flying round and round in front of a dark background.

metre deep, was lined throughout with black velvet. At the bottom of the box a central disc, supported by a footpiece, was placed in position: the periphery of the space was covered with a white material, leaving between it and the central disc an annular track covered with black velvet (Fig. 174). It was round this annular

track that the insect was made to fly. A needle stuck perpendicularly in the middle of the disc served as an axis for a revolving beam and its counterbalance. This beam consisted of a straw, and at the end of it was fixed a light pair of surgical forceps to hold the insect by a part of its abdomen. When thus fastened, the dragon-fly was left to its own devices. It then commenced flying at rather a rapid rate round the track, drawing the straw after it, the movement often persisting for some considerable time. The gold spangle

FIG. 175.—Photographic trajectory of the wing of a dragon-fly.

fastened to its wing described a trajectory which is reproduced in Fig. 175.

The lemniscate described by the insect during its flight in captivity, is no longer to be seen, but in its place there is an undulating curve which presents at different stages of its course a greater or less degree of brightness, according as the inclination of the wing is favourable for the reflection of light or the reverse.

Chronophotography of Insects on Moving Films.—The series of proofs which we have just given appear to us to leave no doubt as to the correctness of our views on the flight of insects.

But although our theory may be generally true, there are still certain details which remain to be elucidated. For instance, in what way does the flight of one insect differ from that of another, and what function do the balancers subserve? Those singular organs which from the point of view of comparative anatomy would seem to be undeveloped wings, appear to be indispensable for the flight of dipterous insects. It occurred to us that these and many problems could be solved by chronophotography, if it only enabled us to catch a momentary view of the insect's

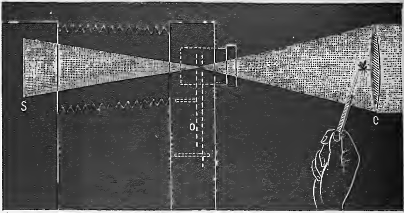


FIG. 176.—Schematic arrangement for illuminating insects when studying their flight.

wing during its flight. But one can imagine that the exposure would have to be very short to procure a well-defined photograph of an insect's wing, when an exposure of $\frac{1}{2000}$ of a second is too long in the case of a bird's, although in the latter instance the movement is much less rapid.

Further, it is not improbable that with such a short exposure, the time would be insufficient to imprint a definite image on the plate. In order, then, to diminish the period of exposure the fenestrations of the rotary diaphragms must be made very small, and the light

that is thrown on the insect very concentrated. Fig. 176 is a general scheme of the arrangement we adopted. In the first place, it will be noticed that there is a parallel beam of light travelling from right to left, and directed by a heliostat towards the principal optical axis of the object-glass. This beam of light is condensed by a lens* (*c*) behind which the insect

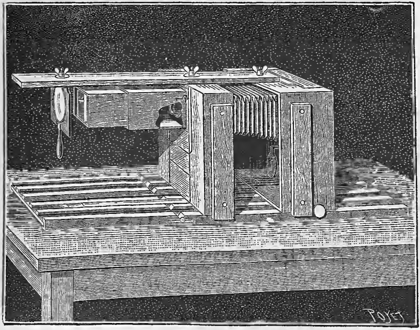


FIG. 177.—Chronophotographic apparatus arranged for studying the natural flight of insects.

can be seen between the points of a forceps. The condensed beam of light traverses the first lens of the object-glass, and the rays are brought to a focus at the circular diaphragms; at the moment two fenestrations coincide the rays can pass through and illuminate the field of the movable film, in the middle of which a silhouetted image of the insect stands out in bold

* The focal length of this lens should be at least double that of the objective.

contrast. We were not very successful in our experiments with all kinds of insects; the method, it is true, allows of the insect being posed at will, and also allows one to obtain photographs of the attitudes of the wings as seen from different points of view, but it gives them an exaggerated appearance both as regards the extent and the rapidity of the movement.

To study an insect in free flight, a cardboard box (Fig. 177) is placed in front of the object-glass, the insect is confined by means of a pane of glass which just touches the condensing lens. Being introduced into this box, the insect immediately flies against the

FIG. 178.—Fly crawling on a window-pane before taking to flight.

glass, which previously should be placed at the focal point of the object-glass. The insect's flight can be watched, and at the desired moment the button can be pressed which sets the film in motion.

Fig. 178 was obtained in this way; it represents a fly crawling on the pane of glass and then taking flight. The exposures were extremely short, as we have previously mentioned, in order that the wings, which moved very rapidly, might be well defined.

With fenestrations 2 centimetres in breadth, the actual exposure being $\frac{1}{2000}$ of a second, the photographs were not distinct, at least not of the extremities of

the wings. So we gradually reduced the diameter of the fenestrations by drawing the metal curtains which regulated the size of the openings.

When the openings in the two diaphragms were only 1·5 millimetre in breadth, the duration of the exposure was reduced to $\frac{1}{25000}$ of a second, and in this case the photographs obtained never failed to be absolutely distinct.

An insect flying against the pane of glass must occupy a considerable amount of space in an antero-posterior direction, and hence if all portions of the body are to be well defined, the object-glass must be one of considerable focal length. Now, as a matter of fact, the extreme narrowness of the fenestration through which the light passes, and the corresponding smallness of the openings of the diaphragms give a focal length of rather more than 2 centimetres.

FIG. 179.—Bee flying about in the chamber of the apparatus.

Fig. 179 shows a bee in various phases of flight. The insect sometimes assumes almost a horizontal position, in which case the lower part of its body is much nearer the object-glass than is its head, and yet both extremities are equally well defined in the photograph.

The successive images are separated by an interval of $\frac{1}{20}$ of a second (a long time when compared to the total time occupied by a complete wing movement, *i.e.* $\frac{1}{190}$ of a second). And hence it is useless to attempt to gain a knowledge of the successive phases of movement, by examining the successive photographs of a consecutive series representing an insect in flight. Nevertheless, an examination of isolated images affords information of extreme interest with regard to the mechanism of flight.

We have seen that owing to the resistance of the air the expanse of wing is distorted in various directions by atmospheric resistance. Now, as the oscillations during flight are executed in a horizontal plane the obliquity of the wing surface ought to diminish the apparent breadth of the wing. This appearance can be seen in Fig. 180. There is here a comparison between two tipulæ: the one in the act of flight, the other perfectly motionless and resting against the glass window.

The motionless insect maintains its wings in a position of vertical extension, the plane is therefore at right angles to the axis of the object-glass. The breadth of the wing can be seen in its entirety; the nervures can be counted, and the rounding off of the extremities of the wings is perfectly obvious. On the other hand, the flying insect moves its wings in a horizontal direction, and owing to the resistance of the air the expanse of the wings is obliquely disposed, and only the projection of its surface can be seen in the photograph. This is why the extremity of the

wing appears as if it were pointed, while the other parts look much narrower than normal. The extent of the obliquity can be measured from the apparent

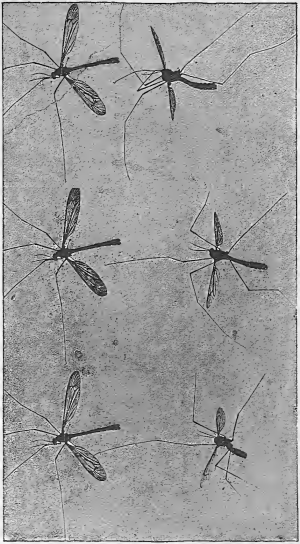


Fig. 180.—Illustration to show two Tipulæ: one of them remaining motionless on the glass, and the other moving its limbs in different directions, and setting its body at various inclinations. The illustration only represents a small part of a long series.

alteration in width, for the projection of this plane with the vertical is the sine of the angle. From this it

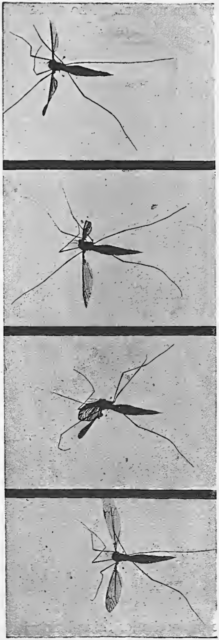


FIG. 181.—Tipula in the act of flying, showing the various attitudes of the wings and the position of the balancers.

may be gathered that the right wing (Fig. 180, 3rd image) was inclined at an angle of about 50° with the vertical, say 40° with the horizontal.

This inclination necessarily varies at different points of the trajectory, and must augment with the rapidity of movement; the obliquity reaching its maximum in those portions of the wing which move with the greatest velocity, namely, towards the extremities. The result is that the wing becomes twisted at certain periods of the movement.

The tortion which was reproduced in the case of the wings of our artificial insects, may be observed in some of the photographs, as, for instance, in the 4th image in Fig. 181.

When the direction of movement varies, the inclination of the plane of the wing varies also, and for a moment this plane must become vertically disposed. This may be seen in the first image of the same figure, for in this instance the wing looks exactly the same size, and has the same appearance, as in the case of the motionless insect.

The balancers can be distinctly seen, and the position of these organs seems to vary according to that of the wings. Careful observation of a great number of photographs taken under different conditions will no doubt determine the nature of the movements of these structures.

Finally, we by no means despair of being able to apply chronophotography on fixed plates to the study of insect movement, and of thus being able to obtain a sufficient number of photographs to demonstrate all the phases of the wing movement.

Some of our attempts have already shown that under certain conditions of illumination, the insect can be photographed as a bright object standing out against a dark background.

CHAPTER XV

COMPARATIVE LOCOMOTION

SUMMARY.—Comparative locomotion among terrestrial mammals: the man, the horse, the elephant—Comparative locomotion among different kinds of birds—Classification of different types of locomotion—Comparative locomotion of tortoises and lizards; frogs, toads, and tadpoles; snakes, eels, and fish; insects and spiders.

Comparative Locomotion. — The most interesting feature of zoology is not so much the descriptive and systematic account of the various forms met with in the animal kingdom as the tracing of association between form and function. As comparative anatomy and physiology become more and more allied, doubtless more fundamental morphological laws will be discovered, and these perhaps will enable us to predict the function of any particular organ from an anatomical inspection.

We are certainly very far from being in a position to understand this association in the case of most organs; but the mechanical action of some of them is already so familiar that the physiological function can be explained on anatomical grounds. The form of the vertebrate skeleton, the volume and length of the muscles, and the relative dimensions of the long bones are necessarily closely associated with the kind of locomotion habitual to the animal. Inviolable mechanical laws govern this association, some of them

have already been enunciated, and we have no doubt that others will soon receive an accurate formulation.

But to determine these laws the character of an animal's locomotion must be as precisely defined as its anatomical structure. Chronophotography, and more particularly the diagrams which it enables us to construct, leave nothing to be desired in point of truthful expression of certain types of locomotion. A few examples will show the value of this method.

Comparative Locomotion among Different Terrestrial Mammals.—A striking feature among terrestrial mammals is the variety of morphological form, and this is equally the case as regards their mode of locomotion. But beneath this apparent diversity, zoologists have discovered profound analogies; only to instance the most obvious of these, the lower limbs of a man evidently correspond to the hind legs of a quadruped, and all through the mammalian series some similarity may be recognized, either as regards limb or bone or muscle. Differences, indeed, exist among different species, but they are chiefly referable to inequality of development, fusion of some parts, atrophy or malformation of others, or to anatomical disproportion. The important point to establish is the connection between anatomical and functional variation.

Now, by means of chronophotography, it is easy to trace among different species the respective movements of the different segments of the limb in walking or running. One animal supports itself on the ground by its digital extremities, another by the entire plantar surfaces of the feet. One animal will progress by means of alternate oscillations of its limbs, another by sudden extension ending in a jump. But the unaided eye cannot determine with certainty the respective parts played in these actions by the various bony segments. Chronophotography, however, shows every

detail with absolute accuracy. Thus the diagrams 182, 183, and 184 represent almost on the same scale the movements of the different segments of the lower

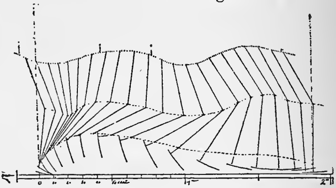


FIG. 182.—Movements of a man's leg in executing a step.

limbs during the execution of half a step in the case of a man, a horse, and an elephant.

These diagrams demonstrate that the same segment can execute different movements, just as it may be of different length and different shape in the three types under comparison, and that the same segment may

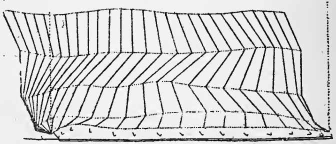


FIG. 183.—Movements of the various segments of a horse's hind leg in executing a step.

play a variable part in the flexion and extension of the limb.

We can now understand why the muscles which act upon these bones present, in different species of animals, differences in length and volume, although the

movement executed may be the same. It is by thus analyzing the types of locomotion proper to a large number of species that the necessary data is forthcoming for determining the association between form and function.*

In returning to the study of man, the significance of individual peculiarities in the structure of the body will make itself apparent. The variation in length of the bones of the limbs, or in the development of certain muscles, so noticeable among certain races of men, connects each human type with some

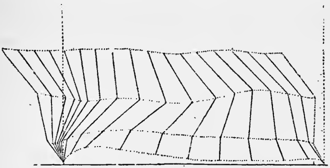


FIG. 184.—Movements of an elephant's hind leg in executing a step.

species of animal with similar characteristics. If, for instance, the development of the gastrocnemius muscle, or extensors of the thigh, in a man suggests a resemblance to a leaping animal, it may be concluded that this man will probably possess special aptitude for jumping, and so on.

Comparative Locomotion among Birds.—We know that there are two distinct types of wing among birds, each suitable for a different kind of flight, the "sailing" flight and the "rowing" flight. Birds that sail possess narrow wings; shorter and broader wings are peculiar to those that use them as oars. If the

* See Marey, *Recherches Expérimentales sur la Morphologie des Muscles.* C. R. de l'Académie des Sciences, September 12, 1887.

area of wing is greatly reduced, the bird can fly no longer in the ordinary way through the air; but it can fly fairly well along the water, like penguins and birds of similar nature. This water-flight may be observed also among certain marine tortoises, the lower limbs of which resemble in shape the wings of a penguin. Further, tortoises and birds have many anatomical resemblances.

The relation between the shape of the wing and the character of flight can be traced as regards other structural details. We have already shown that the volume and shape of the muscles present differences amongst birds which use their wings as sails and those which use them as oars; in the former the muscles are short and thick, in the latter long and slender. Similar differences are to be noticed in the bones of the thorax which are characteristically grooved for the insertion of these muscles.

The differences in flight among the principal types of birds, as far as we have been able to study them, have been demonstrated by means of chronophotography, and it is extremely probable that, by studying a great number of species by the same method, we shall find among the various types of flight, gradations and transitions parallel to those anatomical variations which have been recognized by comparative anatomists among ornithological genera and species.

Classification of Different Types of Locomotion.—It is not always possible to take comparative anatomy as a guide to physiological classification. Sometimes it is the variation or functional analogy which may be most apparent, and which will assist us in discovering the zoological relationship. For this reason we have endeavoured to procure photographs of a great number of different species of animals, so as to collate the various physiological types and classify them like the

sections of a museum of comparative anatomy, in the hope that such a series might be able to throw some light upon the subject. The principal difficulty in this undertaking lies not so much in the actual collection of many different species, as in the subjection of them to the best conditions for observation.

Domestic animals or tame species can easily be dealt with, but the natural paces or movements of others can only be observed under special conditions, the nature of which can only be discovered after patient research.

A frightened animal never moves about in a normal fashion, and if it is compelled to advance in a predetermined direction, it instinctively goes the other way. Sometimes the animal becomes scared by the bright light with which it is necessarily illuminated; at other times it resents an abnormal support under its feet. In some cases the animal has to be brightly illuminated against a dark background, at others it has to be silhouetted against a dark background. In all these cases a straight pathway from which it cannot diverge is essential.

Being compelled to curtail the discussion of these researches, we can only give a few examples of comparative locomotion, and a brief account of the arrangements for taking the photographs.

Comparative Locomotion of Tortoises and Lizards.—A water tortoise was placed in a glass aquarium and exposed to translucent illumination, just as in the case of the sea-horse described (p. 212). The animal dived and crawled about at the bottom of the aquarium, but after a time it had to rise to the surface for breath, and it was this movement of which advantage was taken.

Fig. 185 shows the tortoise moving about like a quadruped in water, the successive movements of the

four limbs being characteristic of an ordinary walking pace.*

Having taken breath, the tortoise returned to the bottom of the aquarium by a similar mode of progression.

With other species, the marine turtle, for instance, there are two distinct kinds of locomotion—firstly, that of walking, which has just been described; and, secondly, that which we have compared to flying. In this latter method of progression, the hind limbs are stretched out side by side, and are free from all movement, while the fore limbs are moved backwards and forwards in the execution of movements similar to those of the wings of a "rowing" bird.

The progression of land tortoises appeared to us to

FIG. 185.—Quadrupedal movements of a fresh-water tortoise in swimming to the surface.

resemble ordinary walking, but not having had time to tame a specimen, we did not succeed in inducing one to walk in front of the object-glass; the animal, no doubt frightened at the noise of the apparatus, obstinately kept its limbs tucked away under its carapace.

Lizards are extremely difficult to deal with. To place one under favourable conditions for observation we made use of the circular canal which was represented in Fig. 50, and designed for studying subaqueous movements. The transparent part of this canal was lighted from beneath, and the photographic apparatus was placed at a higher level, and received its images reflected from a mirror obliquely inclined at an angle

* See sequence of these movements in Chap. xi, "The Synoptic Record of Horses' Paces."

of 45°. A lizard was placed on the glass bottom, and silhouetted on the sensitized plate. But grey or green lizards were unable to crawl on the slippery surface of the glass; but, on the other hand, the Gecko with its spatulated digits could run about with ease. That all

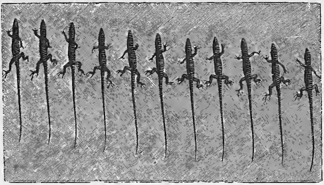


FIG. 186.—Grey lizard. The series must be followed from right to left.

these specimens might be under equally favourable conditions for locomotion a piece of muslin was pasted on the surface of the glass. This muslin should be very transparent, and yet rough enough to admit of

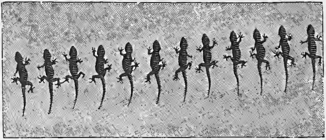


FIG. 187.—Gecko. The series must be followed from left to right.

locomotion. Figs. 186 and 187 show the mode of progression of the grey lizard and the Gecko. Taken as a whole, the paces are similar,* but with the Gecko,

* See chap. xi. Synoptic chart of the characteristics of the equine trot.

which has a shorter body, the track of the hind feet is very near that of the front. Moreover, the movements are extensive, and cause a serpentine twisting of the whole body. As these movements are very rapid, a great number of photographs must be taken—about sixty per second—in order that their sequence may be distinguished.

Frogs, Toads, and Tadpoles.—In accordance with the stage of development, batrachians depend on different types of locomotion.

Before the tadpole's legs are completely developed

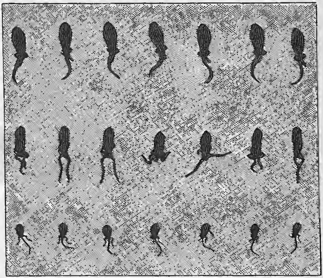


FIG. 188.—Locomotion of batrachians at different periods of development.

it swims with its tail after the manner of a fish (Fig. 188, first row). When the tail has disappeared and the four legs are completely formed, the swimming of batrachians resembles that of man (Fig. 188, second row). The legs, which are at first widely separated, are brought suddenly together, then drawn up under the body, and finally separated again,

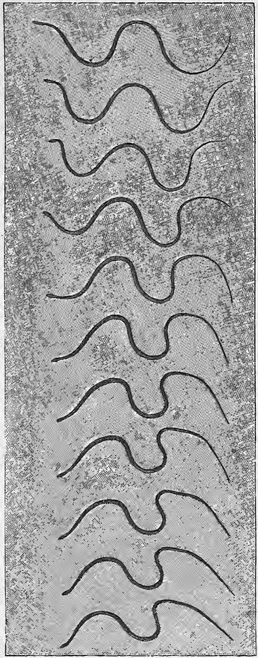


FIG. 189.—Land-snake in motion. Series to be followed from left to right.

so as to give a fresh impetus when they are again suddenly approximated. Meanwhile the fore limbs are pressed against the thorax, and appear to be quite inactive.* In the intermediate stage, when the legs are incompletely developed, and the tail has not yet disappeared (Fig. 188, third row), the batrachian has a mixed mode of progression. Between the hind legs, which execute the movements of swimming, the tail keeps up an incessant wriggling motion.

Snakes, Eels, Fish.—Snakes have a slightly different method of progression according as they are on land or in water. An ordinary adder placed in the dry canal, before described, executes undulations of considerable amplitude (Fig. 189). As the animal moves along, the undulations pass from the anterior to the posterior end of the body, the same as in the case of the swimming eel. A water adder placed in the dry canal progresses in the same manner, as also does an eel. But when these same animals are placed in water, they swim about with an undulatory movement of less amplitude, but with far greater regularity. Fig. 190 represents an eel in the act of swimming; the method of progression is identically the same as that of the adder, except that the movement of the tail is more accentuated. The tail of an eel is transversely flattened, and imparts a movement like that of other fish; the undulations of the tail are, however, more pronounced than those of the rest of the body.

Among other fish the undulations of the body are less marked, although very noticeable in the case of the dog-fish, which is a long-bodied animal (Fig. 191). It is to be observed only in the tail in some species, the movements of the body being but slightly developed, as, for example, is the case with the Cyprinidæ.

* Owing to a mistake in the engraving, the order of the images has been changed in several instances on the second line of figure.

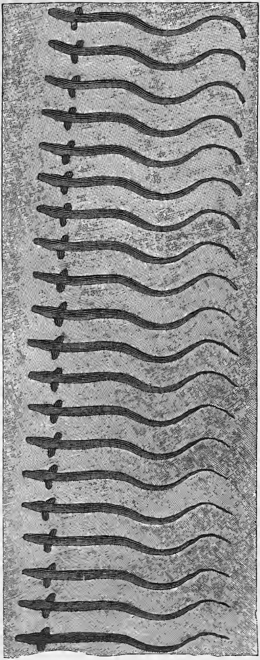


Fig. 190.—Eel swimming. Series to be followed from right to left.

Insects and Arachnids.—Among six-legged insects and eight-legged arachnids the variations in the methods of progression are entirely due to the different number of legs. In these species the separate legs of each pair act alternately, and the movements of one pair alternate with those of the next. It follows, as was carefully observed by Carlet and M. de Moor,*

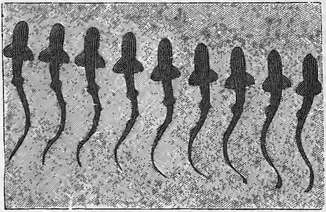


FIG. 191.—Dog-fish swimming.

that among the Coleoptera, for instance (Fig. 192), the first and last appendages on the same side are in contact with the ground, while the middle one is raised. On the other side of the body the middle appendage is on the ground, and the first and last ones raised.

When an insect turns round, the movements are feebler, or cease altogether, on the side towards which the animal turns.

In the case of certain insects which jump as well as

* De Moor (*Archives de Biologie Liège*, 1890). The author gives a very complete account of his studies made on the locomotion of insects. He describes how he obtained the track of each of the feet in different colours by coating them with different pigments; the insect, as it moved, left its track on a strip of paper. He also describes how he arranged the light so as to best observe the movements.

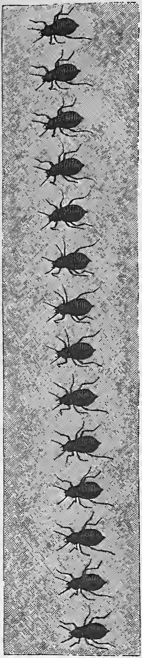


FIG. 192.—Beetle walking. Series to be followed from left to right.

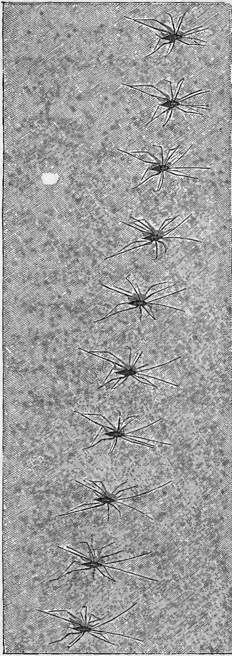


FIG. 193.—The walk of an orthopterous insect. Series to be followed from right to left.

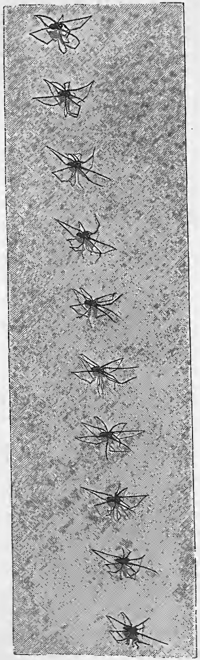


Fig. 194.—The walk of a spider. The series to be followed from left to right.

crawl we have not been able to make out how the sudden spring of the hind legs is effected, but they crawl much in the same manner as Coleoptera, as may be seen in Fig. 193, which represents an orthopterous insect.

Among the arachnids (Fig. 194) the four feet of each side alternate in their movements, so that there are always two feet off and two feet on the ground, as can be seen in the case of the spider.

To distinguish the feet on the ground from those which are raised we illuminated an insect from above, so that the shadow of its legs was projected on to the white surface upon which it crawled. Under these circumstances the shadow of each foot which was in contact with the ground extended right up to the foot itself; on the other hand, when the foot was raised, a gap existed between the foot and its shadow.

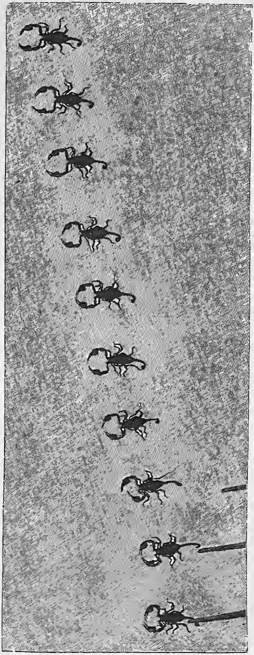


FIG. 195.—The walk of a scorpion. Series to be followed from left to right.

Scorpions move very rapidly; their progression is due to a series of sudden springs, which can be provoked by excitation. The sequence of movements is so swift that we have found it impossible to determine their nature by means of photography (Fig. 195).

All these insects moved about on glass covered with paper or transparent muslin, and were viewed by translucent or reflected light. Their movements were directed by means of two sheets of glass, which were arranged so as to be parallel and vertical, and thus to prevent them from leaving the desired track. These few examples will suffice to show how to collect and compare from various species of animals chronophotographs of different types of locomotion. In a collection of a great number of photographs of this kind one will find the necessary elements for the study of comparative physiology, a study which we mean to pursue.

CHAPTER XVI

APPLICATIONS OF CHRONOPHOTOGRAPHY TO EXPERIMENTAL PHYSIOLOGY

SUMMARY.—Numerous applications of chronophotography; it supplements the information derived from the graphic method—Study of the movements of the heart by means of the graphic method—Photography of the successive phases of cardiac action in a tortoise under conditions of artificial circulation—Variations in shape and capacity of the auricles and ventricles during a cardiac cycle—Mechanism of cardiac pulsation studied by means of chronophotography—Comparative advantages of mechanical and chronophotographic registration—Determination of the centres of movements in joints.

ALMOST all vital functions are accompanied by movement; but any attempt to investigate them is beset with extreme difficulty, for the majority of them are very complicated or very rapid. Sometimes, on the other hand, they are extremely slow and difficult to observe.

The methods employed by physiologists are generally devised with a view to elucidate what the unaided eye cannot discover for itself.

It might reasonably be predicted that chronophotography might be found useful in this domain. It might show, for instance, the part played from moment to moment by the different parts of the thorax in the act of respiration. It might follow the peristaltic and the antiperistaltic contractions of the intestines through all their phases and under the various conditions which modify the characters of these movements. In a word,

it might be used in all cases in which neither ordinary observation nor the employment of the graphic method could give us any definite information.

There are also many curious movements in the vegetable kingdom which can be studied by means of chronophotography, such, for instance, as the sudden retraction of the leaves and petals of the sensitive plant when touched, the gradual return of these structures to their original position, the progress of vegetable growth, the unfolding of leaves, and the blossoming of flowers.

Successive photographs, taken at more or less frequent intervals of time, will show the various phases of these phenomena.

In both kingdoms the microscope reveals deep down in the midst of living tissues movements of immense interest, for they are concerned with the fundamental principles of organic life. Of such a nature is the circulation of blood corpuscles in the finest capillaries, and such is the movement of the zoospores in the cells of algæ; such is the slow alteration in shape of the white corpuscles of the blood, and the phenomenon of phagocytosis, etc. It would be a very interesting study to ascertain the characters of these movements by means of photography.

To give an instance of the advantages of chronophotography as applied to an experimental problem in physiology, we will take the case of cardiac movements. This is a subject which has been exhaustively studied by means of the graphic method; nevertheless, chronophotography has afforded much new information of quite a different kind; we will summarize the question as it stands at present.

Analysis of Cardiac Movements by means of the Graphic Method.—About thirty years ago, we, together with our friend and colleague Chauveau, suggested at

the Academy of Science and at the Academy of Medicine a theory of cardiac movement, based upon information derived from the graphic method. This theory, to-day universally accepted, put an end to differences of opinion among physiologists and physicians, and it has not been unassociated with recent advances in the diagnosis of cardiac and vascular diseases.

We were induced to embark on these experiments by the incomplete evidence derived from direct examination regarding the nature and sequence of the extremely complicated movements, executed by the heart from moment to moment during a complete cycle of events.

Our method was indirect, and consisted in registering the curves of pressure variations occurring in the interior of the cardiac cavities as well as outside these chambers. Our curves, properly speaking, did not explain the movements of the heart; but, nevertheless, they enabled us to state the order and sequence of the auricular and ventricular movements from the changes in pressure which they expressed.

This interpretation was often a very difficult task, and required a considerable number of experiments in order to verify the different points at issue. Although it was pretty evident that the maximum of pressure in each cardiac cavity corresponded to the moments at which these cavities contracted for the expulsion of the contained blood, yet it was by no means easy to discover the significance of each variation on the cardiographic curves.

Let us examine tracings which express the alterations in blood-pressure in the auricles and ventricles, and the phases of cardiac pulsation. If these figures were placed before the eyes of a physician, whom we will suppose ignorant of the physiology of

the heart, he would derive from the curves an exact knowledge of the blood-pressure obtaining in the cardiac chambers, and of the ever-changing force to which the exploring apparatus was exposed in its contact with the ventricular walls. Further, he would notice the exact sequence of these changes: but from these curves alone he would gain no information concerning the organ which brought about these changes. It would be possible for him to picture to himself a system of pistons, pumps, and valves capable of producing similar results, but he would never succeed in realizing the actual shape of the heart and the alteration in appearance and volume which the different cavities of this organ present from moment to moment.

Further, as no analogous phenomenon is to be found outside the animal kingdom, the physician would doubtless be at a loss to understand the mechanism of the ventricular contractions, namely, the centrifugal impulse given by the organ at the moment of systole.

Even physiologists must acquire some preliminary knowledge, by means of vivisection, of the shape of the heart and its peculiar movements before they can understand the real significance of a cardiogram; but our eyes are hardly capable of following the rapid and complicated variations presented by a heart in motion, the shape of the various cavities whether being filled or emptied, the moment of distension of the blood-vessels of the heart, or the contractions of the muscular fibres, etc.

As soon as we had at command a method of chronophotography which faithfully interpreted the changes in shape and position of moving bodies, we sought to derive from this method information supplemental to that furnished by the graphic method. The following experiments were our first attempts in that direction.

Photography of the Successive Phases of Cardiac

Action in a Tortoise under Conditions of Artificial Circulation.—As we had no large animals at our disposal in which the movements of the heart were accompanied by such strange variations in appearance, we were compelled to analyze the movements of a land tortoise's heart by means of chronophotography.

In order that the entire heart might be visible, we removed it from the body and placed it under conditions of artificial circulation.* Then, in order that the various parts of the circulatory apparatus might be confined to as narrow limits as possible, the apparatus was simplified as represented in Fig. 196.

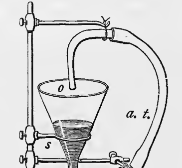


FIG. 196.—Heart of a tortoise under conditions of artificial circulation. *a*, auricle; *v*, ventricle; *a. t.*, arterial tube; *o*, outflow; *s*, support of the funnel, which represents the venous system and its communication with auricle.

The narrow end of a glass funnel was introduced into the vena cave close up to the left auricle, and fixed there by a strong ligature. Then a glass canula was introduced into the aorta, and connected with a piece of indiarubber tubing to represent the artery; this tubing in turn was connected with a piece of glass tubing bent at an angle (*o*), the opening of the latter was directly above the glass funnel. The whole of the apparatus was placed on a solid support, and allowed to stand out in relief against a light background.

* For the description of the method, see Marey, *La Circulation du sang à l'état Physiologique et dans les Maladies*, p. 70, Fig. 28. Paris, G. Masson, 1881.

Some defibrinated bullock's blood was poured into the funnel so as to fill it three parts full. After a few minutes, the blood was seen to fill the auricle, and then almost immediately to be discharged into the ventricle; the latter, in its turn, contracted and sent its contents through the tube, from which it was emptied into the funnel through the attached pipe.

Instead of the weak and occasional movements executed by the heart when depleted of blood, an energetic circulation was established, and continued from six to ten hours, and sometimes even longer, the time being dependent on the season of the year. Under the influence of the heart's activity, the blood soon assumed a veinous character, and therefore it was found essential to renew it from time to time, in order that the energy of the artificial circulation might be maintained.

The photographs thus obtained can only be represented as shadows, because the red colouration of the tortoise's heart is not photogenic, and cannot, therefore, form an image by reflection, and give the configuration which is necessary for understanding the changes in form of the auricles and ventricles, which occur from moment to moment.

These silhouettes, however, enable one to follow the various stages by which the blood circulates through the heart, and the tubes which communicate with the cavities of that organ. As the photograph represented in Fig. 197 has to contain several images, we reduced as far as possible the component parts of the apparatus for carrying on the artificial circulation. The broad funnel in Fig. 196 has been replaced by a thick glass tube pointed at the end, so as to pass through the vein and gain entrance to the auricle. This constitutes the veinous reservoir. Another and finer tube, representing the artery, fits into the orifice

of the aorta, and curves round, so as to pour its contents into the veinous reservoir.

In following the chronophotographic images which correspond to the successive phases of the cardiac cycle, the series must be read from left to right. It will be noticed at once that in the first position no blood is passing into the veinous reservoir through the arterial tube, the ventricle is consequently relaxed (diastole).

The positions, 2, 3, 4, and 5, show a jet of blood flowing into the reservoir, the ventricle is therefore

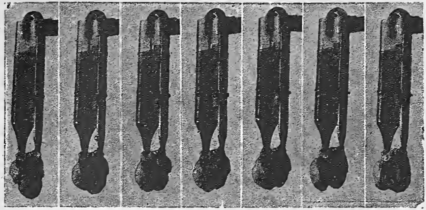


FIG. 197.—Seven successive photographs of a tortoise's heart with artificial circulation. The series must be read from left to right. They are taken at intervals of $\frac{1}{10}$ of a second. In each member of the series the auricle is on the left and the ventricle on the right. From the 2nd to the 5th image the ventricular systole may be recognized by the stream of blood which pours into the venous reservoir.

contracted (systole). Finally, positions 6 and 7, in which the jet of blood can no longer be seen, represents a fresh diastolic period. The same phenomena continue indefinitely, and pursue the same sequence of events as already described.

The series of positions might, therefore, be transposed, with No. 1 immediately following No. 7.

As for the heart, nothing but the contour can be seen, and this indicates the alternate dilatations and contractions of the auricle and ventricle.

The auricle, which commences to fill in the 2nd position of the series, is in process of contraction during the 6th, 7th, and 1st. Now, during the stage of auricular contraction, the ventricle may be seen gradually filling, so that in position 1, when the auricle has reached the climax of its contraction, the ventricle has attained to its maximum of repletion. The alternations between the diastolic and systolic periods of the two chambers of the heart are therefore perfect.

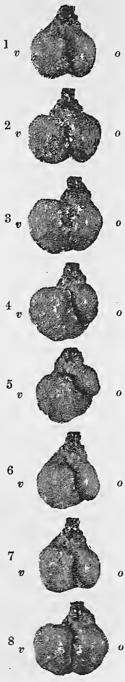
The duration of these phases can be calculated almost exactly from the number of positions which correspond to each stage. The apparatus produced 10 images per second, and since 7 images sufficed to represent an entire cardiac cycle, the latter may be concluded to last $\frac{7}{10}$ of a second. In the same way to the systole of the ventricles may be assigned a duration of $\frac{4}{10}$ of a second, and to the diastole $\frac{3}{10}$*.

These primary notes on the changes in shape of the cavities of the heart will be supplemented by the following experiment.

Variations in Shape and Capacity of the Auricles and Ventricles during a Cardiac Cycle.—The surface of the heart can be rendered photogenic by means of a very simple device; it suffices to paint it with rather a thick coat of Chinese white. The heart being rendered thus quite white, the play of light and shade displays the alterations in shape and capacity of the different cavities. If a chronophotograph be taken of such a

* These measurements do not pretend to rival in exactness those derived from the graphic method, which are almost infinitely accurate. When the commencement and termination of a phenomenon is measured by means of a discontinuous series of images, there may be an error as regards both these stages. The commencement and termination may occur between two exposures of the photographic plate, and it is impossible to say exactly when they occur.

FIG. 198.



On observing the series from above downwards, the following phenomena are observed:—

1. The ventricle, *v*, has completed its systole, and has diminished in volume. The auricle, *a*, is full, enlarged, and shiny.

2. The auricle has commenced to empty itself and change its form; its external surface is flattened, and exhibits two irregular borders and a rounded extremity, giving it a tongue-like appearance. The ventricle is beginning to enlarge.

3. The auricle has diminished in size, and the extremity is approaching the ventricle; the latter is becoming still larger.

4. The auricle is still contracting, and the ventricle is approaching its maximum of repletion.

5. The auricle has completely emptied itself, and the ventricle is diminished in volume; its systole is commencing (at this moment the blood is being poured into the reservoir).

6. The ventricular systole continues, and the relaxed auricle commences to fill.

7. The ventricular systole is completed, the auricle is distended and shiny, and the phase represented in the first of the series is repeated.

heart, which, for convenience' sake, should not be obscured by complicated apparatus, it will give a series of positions which may be studied in detail. Some of the most important points learnt from examining such a series are as follows:—The cavities of the heart have each their peculiar shape, and as the blood pours in they do not assume such a rotund appearance as would be presented by a homogeneous and elastic sac, but, take on various forms, apparently conditioned by the unelastic nature of the pericardium, by which the auricles and ventricles are confined, and generally compressed. Consequently, the outer surface of these cavities appears convex, and moulded to the concavity of the pericardial sac. The adjacent sides of the chambers are flattened against one another, producing facets and more or less uneven ridges. The facets are not always equally visible: on the ventricle, for instance, only one facet can be distinctly seen just at the moment when it is uncovered by the increasing contraction of the auricle. These distinctions are gradually effaced during the systole. The ventricles then become speroidal in shape, proving that all sections of the wall contribute an equal share in the compression of the contained blood.

Another fact, which such a series of photographs teaches us, is that the diastole of the ventricles coincides exactly with the systole of the auricles. The filling of the ventricle depends, so to speak, on the auricular systole.

We recommend an examination of such a series to those who still believe in an active diastole—a sort of aspiration of the blood by the ventricles—a strange belief, not to be explained by the structure of the heart, and which the action of the auricles renders perfectly useless.

Mechanism of Cardiac Pulsation studied by means of

Chronophotography.—We have already explained this phenomenon as due to the sudden hardening of the ventricles, which, although relaxed and tensionless during the stage of passive filling, become more or less spherical and hard when active contraction begins, they then actually exercise pressure on the blood which has previously distended them. This theory alone accounts for all the phenomena which can be observed; it explains why the pulsation of the heart is perceptible at all points of the surface of the ventricle, it renders the fact intelligible, which appears at first paradoxical, namely, that the heart presses against the thoracic parietes, not when it expands, but when it diminishes in volume. It is not by an alteration in volume, but by an alteration in hardness, that the heart repels everything that has a tendency to compress it. The maximum degree of hardness corresponds, as we before mentioned, to the systole of the ventricles, namely, at the moment when their powerful muscular fibres compress the blood and project it into the arterial system.

Such is the mechanism which causes the sudden pulse which feels like a shock to the finger, and which we call the pulsation, to suggest an analogy between it and the pulse at the wrist; that it consists of a sudden rise in tension in the organ can be proved by touching its hardened surface with the finger.

This theory becomes more intelligible if the ventricles of a large animal are held in the hand; if they are compressed by the fingers, there is a distinct sense of resistance at the moment when the surface of the heart is made tense, which intimates that the systolic contraction of the muscular fibres is in process.

We endeavoured to render this phenomenon visible to the eye by the following experiment, in which we made use of an arrangement of this kind. The

apparatus, as depicted in Fig. 197, for carrying on an artificial circulation, was employed; but the whole of it was obliquely inclined and secured to a bevelled cork by means of modelling wax. The heart, Fig. 199, was then placed on a horizontal stand resting on one of its surfaces, while the other was freely exposed to view, so that the pulsation might be examined.

To prove our point, it must be shown that, when a solid body is pressed against the ventricular wall with a certain amount of force, the latter, during a condition of relaxation, is indented, and allows the solid body to sink into the hollow thus formed; and

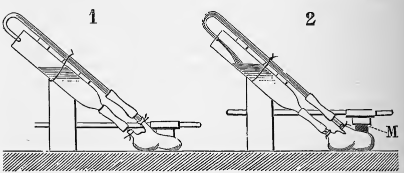


FIG. 199.—Experiment for showing by chronophotography the mechanism of cardiac pulsation.

that, on the other hand, during systole, the ventricles repel this body, and efface the depression.

For this purpose a small square of cork (M, image 2) is allowed to rest on the surface of the ventricles, and a lever with a counterpoising disc is balanced on the cork. The ventricle receives an indentation from the external pressure, and the cork partially disappears within the depression, as shown in the first position of Fig. 199.

This is because the diastole of the ventricles is in process of operation, as may be recognized by the absence of the jet of arterial blood. In position 2

of the same figure, the ventricle is in systolic contraction, which is evident by the flow of blood into the reservoir. Now, at this moment the entire square of cork comes into view, expelled from the depression into which it had sunk when the ventricle was relaxed.

Comparative Advantages of Mechanical and Chronophotographic Registration.—To continue, these experiments, which constitute some of the first applications of chronophotography to experimental physiology, give additional information concerning the functions of the heart over and above that derived from ordinary cardiography. In comparing the two methods, it will be seen that they attain different ends. The one by means of variations in a curve expresses the minutest changes in blood-pressure that occur in the cardiac chambers, and indirectly this reveals the smallest details of cardiac function. But this method only appeals to the initiated; it requires numerous control experiments so that one may fully understand the meaning of the cardiogram. The other method, strictly speaking, is the direct examination of the movements of the heart by a more subtle eye than ours, and one that is capable of grasping in a moment the sum total of the changes which take place in the different cavities of the heart. The information to be derived from this method is self-evident. The comparison of a series of consecutive images also affords an opportunity of observing every visible phase of the phenomenon. It affords us no information, as does the cardiogram, concerning the energy which primarily conduces to the changes in form; in fact, it only gives an approximate idea of the sequence of the various phases of movement, because its record is one of intermittent indications, instead of the continuous record of a curve. Nevertheless, important discoveries

in the realm of physiology may be looked for from chronophotography.

Movements which, in the case of the small heart of a tortoise, have only been sketched in outline, should be more fully studied in the case of large-sized tortoises, for the photographs would be larger and more instructive. Better still to operate on the heart of large mammals, proceeding in the orthodox manner by opening the thorax and inducing artificial respiration. If the heart then be whitened as before described, and a strong beam of light directed on the organ, photographs can be taken containing details not to be found when the hearts of small animals are employed. For instance, one may observe the prominence caused by arteries and veins, the muscular fasciculi, the folds of the serous membranes, and the displacements of the heart within the cavity of the pericardium, etc.

The effects of electrical or other excitation applied to the different points of the surface of the heart can be estimated with extreme precision. Graphic registration and chronophotography give, therefore, very different kinds of information concerning the heart, but both are equally useful. Just as auscultation and percussion, though they greatly differ, nevertheless contribute with equal efficiency towards the diagnosis of the physical condition and the functional adequacy of the heart.

One could indefinitely multiply examples of the various applications of this new method to experimental physiology. We have already mentioned a few in passing; but chronophotography enables us to determine the function proper to each muscle in the act of locomotion, by observing the prominence caused by the muscle in contracting during the various phases of the movement.

But if there is one question more obscure than

another, it is the determination of the centres of movement of a joint.

Determination of the Centres of Movement in Joints.—When two articular surfaces move on one another, the movement does not always take place round a point corresponding to the centre of curvature of the surfaces. We know, for instance, that in the case of the knee-joint the condyles of the femur simultaneously rotate and slide on the articular surfaces of the tibia, and that the condyles of the lower jaw slide in various directions in the glenoid cavity of the temporal bone, etc. It must follow, therefore, that the centre of articular movement is not indicated by the anatomical relations, but must be empirically discovered.

This problem is almost identical with that which is disposed of in regard to the rolling of ships, and the same means may be employed for the experimental solution. On the cadaver the matter is simple: a hole is drilled in the condyle of the inferior maxilla, and another in the ascending process of the same bone near the lower extremity. A polished metal wire is stretched between these two points; in the photograph it will be represented as a bright line indicating the axis of the ascending portion of the inferior maxilla.

The skin of the subject is slightly blackened, and a series of photographs taken on a fixed plate while the jaw is worked up and down. The lines stand out clearly in the photograph, and cross each other at the points which represent the temporary centres of movement of the bone during its angular displacements.

On the living subject the experiment is not much more difficult. A small "planchette" applied to the teeth of the lower jaw is kept in position by elastic bands passing under the chin. Into this "planchette,"

which follows all the movements of the bone, a bright metallic wire is fixed, and bent in such a manner as to correspond to the angle of the jaw; it is cut off short at the level of the condyles.

All the maxillary movements are reproduced by the wire, the upright end of which indicates by its intersections on the photograph the centres of articular movement.

The applications of chronophotography for analyzing such movements as occur within the field of the microscope will probably be of great importance. Our efforts in this direction will be recounted in the following chapter.

CHAPTER XVII

MICROSCOPIC CHRONOPHOTOGRAPHY

SUMMARY.—Various movements observable within the field of the microscope—Applications of chronophotography to the study of these movements—Difficulties of the subject—Special arrangement of the apparatus for chronophotography on fixed plates and on moving films—Retraction of the stalk in vorticella—Movement of the blood in capillary vessels—Movements of the zoospores in the cells of conferva—The use of the solar microscope in chronophotography—The easy application of this method.

THE microscope has been found of use in all branches of natural science, and by it the observer can fathom the minutest structural details of an organ, and can study in certain of their component cells movements which are the very essence of their activity.

Although Harvey, by a flight of genius, concluded that arterial blood returned in some sort of way by the veins, the actual demonstration of this passage was not effected until the invention of the microscope. The whole secret was then suddenly revealed to the astonished eyes of Malpighi—the presence of corpuscles in the plasma of the blood, the capillary ramifications of the vessels which contained it, and the vagarious current which left the arteries and effected its return by way of the veins.

The contraction of muscles was inexplicable until the use of the microscope revealed the existence of muscular fibres, their shortening by means of an aggregation of the component discs, and the wave

that travelled along the length of the fibre during the act of contraction. Since that time physiologists have no longer gone astray after hypothetical "veins"; it is in the actual fibres of the muscles that they seek the origin of mechanical energy in animals.

Facts accumulate—little by little the theory unfolds itself, and the moment is felt to be fast approaching when muscular contraction will be a fully explained fact.

The microscope shows us in a drop of water the animate motion of a million minute organisms roaming about with curious modes of locomotion—methods which find no counterpart among the more highly developed animals.

The pulsation of the heart can be seen through the transparent integuments of certain larvæ; so, too, can the contraction of the intestine, the curious phenomena connected with generation, and the slow metamorphosis of the ovum or the embryo.

The chemist himself, as he watches the beautiful crystalline arborizations developing upon the microscopic slide, essays to interpret the laws of this mysterious architecture.

All these movements, however slow or however rapid be the process, can be followed in their respective phases by means of successive photographs, no less clearly than they can be viewed under the microscope.

Applications of Chronophotography to the Study of these Movements within the Field of this Microscope.—Our own instrument is the only one up till now which can be used for taking a photographic series of microscopical objects. Since our instrument is only provided with one object-glass, the latter must be of suitable focal length for forming images on the sensitized plate of such a nature that they can be enlarged to any degree. The process of microphoto-

graphy has of late years been brought to a high standard of perfection, and apparently at the present time it is only necessary to follow the rules laid down in the various treatises on the subject. In the practical application, however, difficulties arise the causes of which are not far to seek. They consist principally in the illumination of the object.

Very small organisms generally move at a rate quite disproportionate to their size. Infusoria cross the field of the microscope in a moment, and execute an immense number of movements which the eye cannot follow. The vibrating cilia, for instance, which serve as locomotor appendages in many of these animalcules, vibrate with such rapidity that they are absolutely invisible, and only come into view when the animals are dead.

To obtain, therefore, distinct photographs of these movements, the exposure must be extremely short. We have already learned that, to obtain photographs of the wings of an insect during flight, the exposure must be reduced to $\frac{1}{25000}$ part of a second, and that, too, under conditions of brilliant illumination; in fact the insects were photographed in silhouette against the disc of the sun itself. For microscopic creatures, even this illumination would be altogether inadequate, in view of the extremely short exposure necessitated by the rapidity of their movements. It is no longer possible to photograph the object to actual scale, it must be enormously magnified, and this magnification entails a corresponding diminution of the light which reaches the sensitized plate.

A linear magnification of 100 diameters reduces ten thousand-fold the intensity of the light distributed over the plate.

It is true that with powerful lenses the solar rays can be sufficiently condensed, but then the heat which

accompanies this light would soon destroy the living creatures which move about in the preparation. The employment of vessels containing a solution of glycerine and alum has been regarded as the best means of arresting caloric rays; it is, however, altogether inefficient, and so we have resorted to a special arrangement of our own. Instead of allowing the light to shine continuously on the preparation, it was projected in an intermittent fashion, and only allowed to act for a very short duration, generally less than $\frac{1}{1000}$ part of a second.

By this method, no matter how great the condensation of the heat, it could never inflict an injury on the creatures under observation.

Chronophotography lends itself most happily to these instantaneous illuminations.

It is quite sufficient to place the object under examination behind the circular diaphragms. The function of those discs from that time forward is to intercept the luminous rays, which would otherwise reach the preparation, and only to illuminate the latter during the short intervals when the fenestrations in the two diaphragms coincide.

Fig. 200 shows the principal parts of the special apparatus which is adapted to the chronophotographic camera for the analysis of microscopic movements.

A wooden box with a central aperture slides into the front part of the apparatus like the frame for containing the object-glasses which has already been described.

This box contains an object-glass, C, in its anterior portion for condensing the light which reaches it from the heliostat. The focus of this condenser is arranged so as to fall upon the plate *p*, at the same spot at which the preparation is to be placed. During the process of focussing, the position of the plate carrier

is the first to be arranged, and this is carried out by means of the knob B, which controls a rack, and finally by the long rod *mv*, which turns a micrometer screw.

The microscopic object-glass O is then brought to bear upon the preparation.

The rays from the object then cross a square metallic

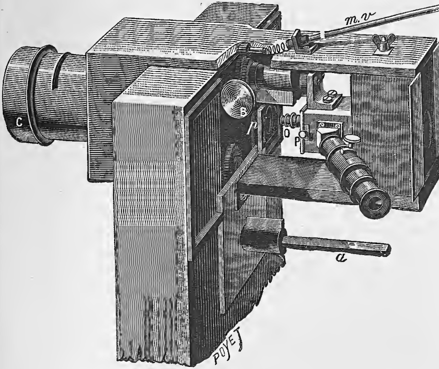


FIG. 200.—Special apparatus adapted to chronophotography for studying the movements of microscopic specimens.

box behind the lens, and finally traversing the wooden box, and the bellows attached, reach the ground glass of the image chamber.*

From the side of the metallic box the tube of a microscope runs obliquely, and is provided with an ordinary eye-piece. By an arrangement invented by M. Nachet, the image can be projected either on to

* For the description of this chamber refer back to p. 116, Fig. 80.

the ground glass or along the tube of the microscope according as desired. This arrangement consists of a refracting prism, which is set in motion by the knob P.

On pressing this knob, the prism is brought into play, and the image of the preparation is projected along the tube of the microscope; on pulling the knob out, the prism is removed and the image falls directly upon the ground glass or upon the sensitized plate.

As it would be impossible to search for interesting parts of the preparation from behind the apparatus by watching the image upon the ground glass, this portion of the operation is effected by looking through the eye-piece of the obliquely placed microscope. The eye-piece can be adjusted by means of a correcting lens, in such a way that the image is always in focus on the sensitive plate when it is in focus as viewed through the eye-piece. The focussing is carried out as follows, a screen of fairly thick paper is placed in front of the condenser so that the light passing through it does not heat the preparation, and at the same time the eye applied to the microscope can easily stand the illumination.*

When the process of focussing is complete and the movements are ascertained to be under favourable conditions, the circular diaphragms are rotated so as to obstruct the continuous light, the screen is removed, the prism drawn away, and the camera set in order for taking a photograph. In this case, as in the other experiments described, it is as well to take some photographs on fixed plates. The moving object must be strongly illuminated in front of a dark background. For slight degrees of magnification

* It would be very imprudent not to use the screen, and care should be taken that it is not removed during the process of focussing; the blinding light which might otherwise strike the retina would be attended with grave consequences.

M. Nachet has constructed a condenser in the form of a cone with a spheroidal base. This base is hollowed out in the middle for the reception of a capsule containing thick black varnish. If the light is thrown on the apex of this cone, it will be reflected in the form of converging rays, and illuminate the objects contained in the preparation, which consequently stand out clearly against the dark central background. But this arrangement is only applicable when the magnifying power is low, and has not up to the present produced any very interesting results. Yet we do not despair of obtaining by some other means a good series of photographs on a dark background, and with fixed plates.

Chronophotography on moving plates is of far easier application, and the first object submitted by us to this method of observation was a vorticella in active movement. This species of infusoria is shaped something like a funnel, and is beset with a crown of vibrating cilia. It is supported on a spirally twisted stalk which is attached by its other extremity to some vegetable fibre, and furnishes a fixed point of support.

From time to time the stalk executes sudden retractions by approximating the turns of the spiral, and the funnel-shaped bell is suddenly brought up to the point of attachment. The stalk then lengthens out, and the spiral arrangement disappears until the following retraction.

Fig. 201 shows, under a considerable degree of magnification, several of these vorticellæ in the midst of a tangle of conferva filaments.

To follow the movement more easily it is as well to take as a guide some fixed point such as the intersection of two filaments selected from the network in the field of the microscope. For instance, in the figure

before us, in the upper half of the left-hand side, there is an irregular rectangle, and in this there are two vorticellæ of unequal size. The larger of them, or that on the left, is situated at about the same level as the other; in the following illustrations it gradually sinks lower down in the field of the photograph, while the turns of the spiral appear more closely approximated.

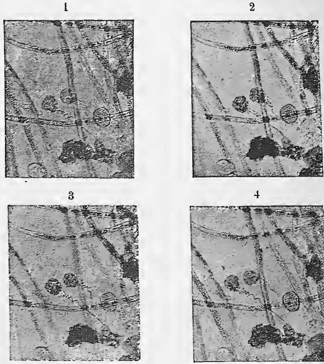


Fig. 201.—Showing the movements of some vorticellæ and the retraction of their spiral stalks. The series must be followed from left to right, commencing with the upper illustrations.

This example is but one of the many interesting ones that could have been chosen, and, moreover, the way in which the figure is reproduced (namely, simili-gravure), necessitates, in the case of such small objects, some alteration in the images. In typography, the shaded parts have to be indicated by *cross-hatching*,

which causes an uncertainty of outline, and an interruption of continuity.

Further, in the reproduction of microscopical photographs, it is always as well to have recourse to thick inks.

The Movement of the Blood in Capillary Vessels.—The capillaries in the mesentery of a triton serve excellently for this purpose. A layer of the peritoneum is stretched over a piece of cork which has a hole bored through the centre, through which the light can penetrate. A fine capillary is manipulated into the centre of the field on the ground-glass plate. Outside the vessel the extravasated red and white corpuscles are motionless, but within the vessel they are hurried along in a rapid but somewhat intermittent stream. If the different members of a series of photographs are compared, it is quite obvious that there is some movement from the changes in arrangement which can be noticed among the corpuscles; the rapidity of movement can be actually estimated by measuring the distance traversed between two successive exposures, namely, the distance traversed in $\frac{1}{20}$ part of a second. For instance, if the space traversed during five separate exposures is about 4 centimetres, say 20 centimetres per second, and the degree of magnification is about 90 diameters, the actual velocity will be a little more than 2 millimetres per second.

Hence, what we call the "circulatory torrent," though it appears very swift to the eye, is in reality a very sluggish stream.

Movement of Zoospores.—In the realm of vegetable Physiology many curious movements are to be noticed; there is one in particular which we thought would be interesting to reproduce, namely, that of the zoospores within conferva cells. These water-plants are composed of filaments consisting of a series of cells

arranged in regular rows, and capable of ramifying in different directions. Some of these cells at certain times are quite full of protoplasm, and in a photograph appear as a dark mass, limited by a transparent cellulose membrane.

Later on, the cells evacuate their contents more or less completely; they are then seen to be reduced to a transparent membrane which is indicated in a photograph as a clear outline. Concerning this phenomenon, botanists have discovered one of the most extraordinary facts in organic life. The protoplasm which at first completely fills the cells as a homogeneous amorphous mass becomes aggregated, and breaks up into a number of portions, each of which develops at one or other extremity a pair of vibrating cilia.

These units take an independent movement, but as long as they are encapsuled within the cell the movement is feeble. As soon, however, as part of the cell wall ruptures, the small bodies escape through the opening and swarm about outside in the water by means of their vibrating cilia. The little bodies are zoospores; it is generally at sunrise that the escape is effected, and the movements during the first hours of freedom are very active.

The movements of the zoospores may be followed throughout by observing in a series of photographs the successive positions they occupy in the mother cell. But no adequate description could be given to those, who have never watched the phenomenon, of the activity which reigns within the cell, and only ceases when all the zoospores have succeeded in effecting their escape.

The Use of the Solar Microscope in Chronophotography.—The practical application of the method which has just been described presents some difficulty

when it is required to observe the movements of certain infusoria as they swarm about in the field of the microscope. Hardly has the presence of these creatures within the field of the microscope been assured before they move out of range and necessitate a new adjustment of the apparatus; for instance, they will disappear during the act of removing the prism which projects the image upon the sensitized film, or while the apparatus is being set in motion. Accurate focussing is difficult to effect because the equalization of the focus of the eye-piece and of the sensitized plate is a delicate operation.

These difficulties may be surmounted by the following contrivance which seems to us to be applicable in all cases. We locate ourselves in a dark room into which the sunlight, reflected by a heliostat, can penetrate through a hole in the shutter. The luminous rays are made to traverse a vessel containing a solution of alum, and to converge on to the preparation by means of a condenser.

The image formed by the microscopic object-glass is received upon a screen. A hole is made in this screen of the same size and shape as the admission aperture, and behind this hole the chronophotographic apparatus is placed.

The front part of the latter is removed and the hinder part is provided with circular diaphragms which rotate in front of the admission aperture. In this way the images of moving creatures can be seen crossing the screen, and the moment can be seized at which these images appear at the aperture; at this moment it is clear that they must be within the field of the sensitized plate which is situated exactly behind.

The knob may be pressed, and a series of photographs taken. If the image is noticed to leave the

opening, and reappear upon the screen, the knob must no longer be pressed, so that the process of taking photographs may cease. When the creatures are again noticed to be in a favourable position, the operation may be continued.

There are many advantages in this method; firstly, it enables the operator to focus more accurately, because he can directly gauge the definition of the image at the moment of exposure; and, secondly, it allows him to avail himself of fugitive phenomena which would otherwise be lost, especially if it is necessary to make rather complicated arrangements before exposing the plate; and, finally, it protects him from injurious exposure to light, in case it should fall upon the retina, a danger which is threatened in other methods, because the light which is thrown by the heliostat, and concentrated by the condenser, may by chance traverse the tube of the microscope.

In this way we obtained photographs of infusoria in motion, the contraction of the internal organs of certain larvæ, the action of the limbs and prehensile appendages of all kinds of microscopic creatures. There even seems a possibility of discovering some curious facts as to muscular contraction from observing certain transparent larvæ.

This method is also well adapted for studying the crystallization of different salts. If a saline solution be concentrated by means of evaporation, crystals make their appearance. There is a special form for each salt, and from these centres of crystallization a variety of arborizations radiate in all directions, and invade the microscopic field with unequal rapidity. The formation of these crystals can be well seen on the screen, and as soon as the edge of the crystalline development is noticed to spread over the admission aperture the photographs can be taken. Each image

shows a differènt phase of development. The incomplete attempts which we have been able so far to make show that microscopic chronophotography would be capable in more practised hands than ours of producing important results. In fact, we propose to continue this line of investigation.

CHAPTER XVIII

SYNTHETIC RECONSTRUCTION OF THE ELEMENTS OF AN ANALYZED MOVEMENT

SUMMARY.—Plateau's method; his phenakistoscope—The zootrope; its applications to the study of horses' paces and their relations to one another—The use of instantaneous photography in connection with the zootrope—Muybridge, Anschütz—Scientific applications of Plateau's method—Points of a good apparatus—Improvements made by different authors—Attempts at constructing a chronophotographic projector.

ALTHOUGH chronophotography represents the successive attitudes of a moving object, it affords a very different picture from that which is actually seen by the eye when looking at the object itself.

In each attitude the object appears to be motionless, and movements, which are successively executed, are associated in a series of images, as if they were all being executed at the same moment.

The images, therefore, appeal rather to the imagination than to the senses. They teach us, it is true, to observe Nature more carefully, and, perhaps, to seek in a moving animal for positions hitherto unnoticed.

This education of the eye may, however, be rendered still more complete if the impression of the movement be conveyed to the eye under conditions to which it is accustomed. Such is the object of Stroboscopy, a method of immense scientific importance. The principles of this method were discovered by Plateau, and

they depend on the physiological property of the retina of retaining for a brief moment the impression of an image after the object which has produced it has disappeared. The duration of this retinal picture is estimated at $\frac{1}{10}$ part of a second. So that if an image is placed before our eyes ten times in a second the idea of discontinuity is lost, and the images appear to be in continual evidence.

If the images shown to us are represented in the successive positions assumed by the object in motion, the impression conveyed to the eye is that of a continuous movement with no intermission. Now, we have seen that not only 10, but even 20, 40, or 60 images can be produced by chronophotography per second. If the 60 photographs taken during one step of a galloping horse could be passed before the eyes at the rate of 10 per second, the duration of the whole step would be spread over a period of 6 seconds, and hence we should have a considerable time in which to observe the motion of the limbs, so hard to follow under normal conditions.

In the same way a flying bird could be represented with slower wing movement, and so too with other phenomena which escape notice on account of their extreme rapidity.

Inversely, when a movement is so slow as to escape observation, photographs could be taken of it at long intervals and presented to the eyes in sufficiently rapid succession to allow of the changes being clearly perceptible. In other cases, if the photographs are presented to the eye at the same intervals as separate the successive exposures, the movement will appear as it actually took place. Such is the use of the stroboscope. We will now show the successive developments of this method.

Plateau's Phenakistoscope. — Everybody knows the

ingenious toy invented by Plateau at the beginning of the present century, and to which he gave the name of "Phenakistoscope."

The original form of this instrument was a plaything which delighted us as children; it was destined,

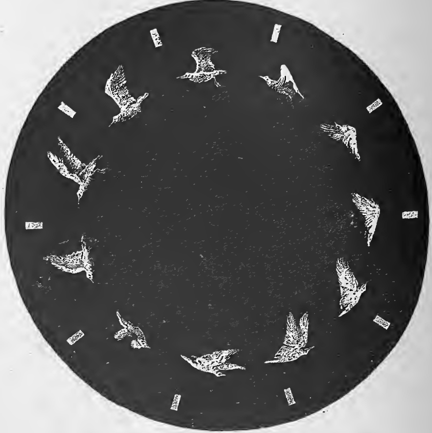


FIG. 202.—Disc of a phenakistoscope, showing the different phases of movement of a gull's wing.

however, one day, to be used for more interesting purposes. The phenakistoscope consists of the following parts, a cardboard disc perforated at equal distances round the periphery by small slits. One side of the disc is blackened, and on the other a series of images

are arranged representing men or animals in the various attitudes which correspond to the successive phases of a movement.

When the disc is spun round on its axis opposite to a mirror, and the eye applied to the blackened side on a level with the revolving slits, the reflections of the various images are seen one after another corresponding to the different attitudes assumed by the original object; this conveys an impression of actual movement. Fig. 202 represents the disc of a phenakistoscope; on it are arranged the successive photographs of a flying gull.

If this side is made to revolve in front of a mirror and the eye be applied on a level with the slits, the gull can be seen flapping its wings. The rapidity of the movement depends on the velocity of rotation.

The disc must be turned in the right direction, otherwise the images will succeed one another in the inverse order to that in which they actually occur, and the direction of movement will appear reversed.

Zootropes.—The manufacture of these articles became a commercial industry, and some of them were turned out in more convenient forms; one of them was called the "zootrope," and consisted of a cylindrical chamber revolving on a vertical axis. Narrow upright slits were made round the brim, and inside the cylindrical wall a strip of paper was pasted on which a series of images was arranged so as to represent the successive attitudes of a man or animal in motion. If these figures were observed through the slits while the zootrope was revolving, the same impression as that caused by the phenakistoscope was produced.

This contrivance, which has been adopted by many manufacturers, possesses one obvious advantage, namely, that several people arranged round the apparatus can watch the phenomenon at the same time.

Application of the Zootrope to the Study of Horses' Paces.—In the year 1867 we made use of the zootrope for the purpose of representing the various paces of a horse in motion, and also for showing how the various paces differed from one another. The latter could be shown by merely altering the sequence of the movements of the fore and hind limbs. This was the concrete demonstration of the sequence expressed by the chronographic charts.

At this time instantaneous photography had not been thought of, and so we used simple drawings to show the successive positions, our data were derived from the registered charts and from the actual foot-tracks.

We chose first the simplest case, namely, the paces of an ambling horse, in which the two limbs on the same side acted simultaneously. Twelve positions were drawn on a long strip of paper, six to represent the rise of the two feet on the right-hand side, the other six to represent their period of contact on the ground, the two feet on the left-hand side were of course in the opposite phases.

By arranging this strip of paper in the zootrope, the paces of an ambling horse could be easily recognized through the slits.

Now, for the purpose of showing how the other paces could be derived from those of ambling, we had recourse to the following device. Vertical lines were drawn through the middle of the horses' bodies, and square frames were constructed round the posterior halves of the figures containing the hind limbs of the animals. The squares of paper were then cut out, and the original strip of paper then remained, representing a series of positions of the fore quarters, and behind each of these mutilated images there appeared a square hole in the paper. The strip of paper was then placed

on another of the same size, and the hind portions of the images which had been cut away were gummed each in its proper position upon the lower strip. When this was done, the two strips taken together presented the appearance of the original slip, namely, the successive attitudes of an ambling horse during the performance of one stride. If the lower strip is moved on one place, so that the fore feet of one image are united to the hind feet of the image immediately behind it, the fore feet will be $\frac{1}{12}$ of a step in advance of the hind feet, and the whole series thus broken up will give the appearance in the zootrope of a racking pace, in which the hind limbs slightly anticipate the movements of the fore limbs.

By sliding the lower strip of paper a little further forward the appearance of a walking pace is produced. Still another move in the same direction and we have a broken trot, and then again a walk.

This is the concrete expression of the relations given by the chronographic chart Fig. 123.

With this method persons familiar with horses' paces can recognize each example, and realize its derivation from the others. We have been most ably seconded in these researches by M. Mathias Duval, now professor at the Faculty of Medicine and at the School of Fine Arts. This savant recognized the importance of this method for teaching complicated and rapid movements such as could otherwise only be learned at the cost of much labour by specialists. M. Zecky, professor at the School of Fine Arts at Vienna, has adopted the same method for representing horses' paces. We still possess some very carefully drawn series which he sent us.

Use of Instantaneous Photography in connection with the Zootrope.—In this method the accuracy with which the paces were represented was entirely dependent on the skill of the artist, and hence it was left for

photography to perfect the zootropic representation of motion.

From the time when Mr. Muybridge succeeded in taking a photographic series of the positions assumed by men and animals in motion, he invariably resorted to Plateau's method for synthesizing the movements he had analyzed.

The apparatus used by Mr. Muybridge was a sort of projection phenakistoscope, in which pictures of horses painted on glass discs, and copied from the author's photographs, were placed in the focus of the projecting lantern and made to rotate. Slits made in the discs admitted light at the required moments. A considerable audience could thus see upon the screen silhouettes of horses moving in various directions and at various paces.

Zootropes of Muybridge and Anschütz.—We have already remarked that the figures were painted. Now, one great disadvantage of Muybridge's apparatus, and, indeed, of the zootrope itself, is that the figures are out of proportion, owing to their reduction in the transverse direction, so that the painted horses on the revolving discs have to be made longer than they really are, so as to appear in their true proportions when thrown upon the screen.

M. Anschütz prepared for the ordinary zoötrope strips of paper covered with photographic prints of men and animals in motion. In this case the figures were distorted; horses especially showed an appreciable diminution in length.

Solid Figures in the Zootrope.—We also made use of the zootrope in studying the movements of birds' wings, and for this purpose we resorted to a particular contrivance. Instead of a strip of paper covered with figures, we introduced into the zootrope a series of wax models painted in oils, and representing the bird

in all the successive phases of its wing movement. The illusion was complete, and a flying bird could be seen flying round and round the apparatus; sometimes flying away from the observer, sometimes across, and sometimes towards him.*

Scientific Applications of Plateau's Method.—All these applications would be simply childish if they were

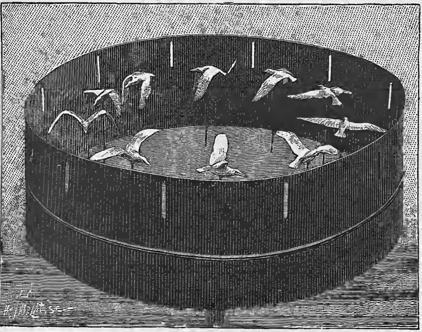


FIG. 203.—Zootrope, with figures of a gull in relief, and in the successive attitudes of flight.

limited to the reproduction of phenomena which could be observed by the eye in the case of living creatures. They would be attended, in fact, by all the uncertainties and difficulties which embarrass the observation of the actual movement. In a bird, for instance, the wings could only be distinguished as an indistinct mass, just

* This zootrope with solid figures is still preserved at the Physiological Station.

as they appear in nature. But a combination of the zootrope and chronophotography has further possibilities, for it enables the observer to follow movements, which would otherwise be impossible to examine, by slowing down the motion to any desired rate. We have already pointed out during a single stroke of the wing, which lasts $\frac{1}{5}$ of a second, a series of twelve photographs can be taken at intervals of $\frac{1}{60}$ of a second. Now, these twelve photographs, which correspond to a single stroke of the wing, can be made to pass before the eye in one second. This succession is sufficiently rapid to produce an impression of continuous motion. Under these conditions, the rate of movement is reduced to one-fifth of its actual velocity, and the eye can follow it in all its phases, whereas, in a living bird, only a confused flutter of the wings can be distinguished.

In the same way, by slowing down the phases of a horse's paces by means of the zootrope, they can be more easily analyzed than by observations made directly on the animal.

It is not, however, only by reason of their rapidity that some movements elude observation, sometimes their very slowness renders them inaccessible to our senses, take, for instance, the growth of animals and plants. These movements may, however, become quite visible if they are photographed at considerable intervals of time, and the corresponding series of images passed rapidly before the eyes by means of the zootrope.

Professor Mach, of Vienna, suggests a curious line of research by means of this method. His idea is to take a number of photographs of an individual at equal intervals of time, from earliest infancy until extreme old age, and then to arrange the series of images thus obtained in Plateau's phenakistoscope. If this were done, a series of changes, which had been brought

about during a period of many years, would pass before the eyes of the beholder in the course of a few seconds, and thus the stages of a man's existence would pass in review before the gaze of the onlookers in the form of a strange and marvellous metamorphosis.

This method invented by Plateau seems likely to extend our knowledge as regards all kinds of phenomena. But the future of the method is dependent on the possible correction which can be effected in the distortion of the images, and on the discovery of a satisfactory means of projecting a number of moving figures on a screen, so as to be visible to a large audience. And, further, it will be necessary to augment the number of successive photographs, so as to represent a performance of considerable duration.

Improvements suggested by Different Makers.—So that the images might be projected without distortion, several object-glasses were arranged in a circle, and at the focus of each positive images were arranged representing the different phases of a movement. All the object-glasses were directed towards the same spot on the screen in such a way that by successively illuminating each of the positive images placed behind them, the corresponding attitudes were successively projected on the screen. To effect the successive illuminations of the slides, it has been suggested that a Drumont lamp should be made to revolve as a source of light.

Images projected in this way ought to be perfect; but the focussing of each, and the determination of the direction of the object-glasses, would be a most laborious operation. Moreover, the number of object-glasses is necessarily limited to five or six, and thus the extent of the movement periodically repeated, as the lamp completes its revolution, is necessarily very short.

M. Raynaud's Praxinoscope.—Under this title, M. Raynaud has given to the world an extremely ingenious instrument. As in the ordinary zootrope, the figures are arranged within a cylinder, and are reflected by a prismatic mirror situated at the centre of the apparatus, and thence reach the eye of the observer. The contrivance is peculiar in that the substitution of one position for another is effected without any intermediate eclipse, so that the images, owing to the constant illumination, appear exceedingly bright. By interposing a photographic object-glass in the path of the reflected images, M. Raynaud has thrown them upon a screen, and magnified them to the required dimensions. Finally, by substituting for the flat circular strip of figures a long strip which winds off one roller on to another, the writer has been able to display a performance of considerable duration. As yet, M. Raynaud has only employed figures drawn or painted by hand; doubtless he could obtain remarkable results by substituting a series of chronophotographs. A slight defect in the apparatus is that the plane of the projected images is slightly oblique as regards the principal axis of the object-glass, this is due to the construction of the apparatus. It is thus impossible that all the parts of the images can be in focus, and hence the projection on the screen is somewhat indistinct.

M. Demeny's Photophone.—M. Demeny has employed another method for reproducing the movements of the face, the tongue, and the lips, executed during speech. My assistant at the Physiological Station has prepared on a length of film a chronophotographic series consisting of twenty-four portraits of a man articulating certain words. When this series of portraits was transferred to the circumference of a glass disc and placed in the focus of a photographic object-glass, they were brightly illuminated from behind, and rendered visible

for brief intervals by an arrangement of fenestrated diaphragms, as used in chronophotography. The shortness of the exposures, and the perfect working of this apparatus, represented the images as immovable, and

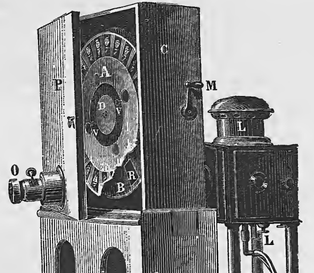


FIG. 204.—Demeny's photophone.

they appeared exactly at the same spot, in spite of the rotation of the disc upon which they were placed.*

These photographs give such a perfect representation of speech that deaf mutes accustomed to read the movements of the lips have been able to recognize the words spoken by the person photographed.

* This instrument was designed by M. Demeny, and called the "Photophone" (*C. R. de l'Academie des Sciences*, July 27, 1891).

I doubt whether it is possible to make a more perfect zootrope, and yet there are a few defects that one can mention. Firstly, the number of images that can be transferred to the disc is necessarily limited, unless the apparatus is of enormous size; and, secondly, since a good definition of the movements can only be obtained by very brief exposure, it follows that the amount of light given off must be too small to produce with distinctness an enlarged projection, and this is the case even when the source of illumination is of the most powerful description.

This list of the different forms of apparatuses used in the synthesis of movement is, no doubt, incomplete; but it may serve to indicate the respective advantages and disadvantages of each system, and to serve as a guide to those who may wish to make fresh researches in the same direction.

The Points of a Good Apparatus.—In apparatuses in which the figures rotate with a continuous movement the image can only be made to appear motionless by giving such a short exposure that the movement during that time is inappreciable.

Now, the brevity of the period of illumination entails a considerable loss of light, and hence the image, when projected on a large scale, is hardly visible at all. If, on the other hand, it is necessary to produce a brilliant projection, the duration of the exposure must be as long as possible; in that case, however, the image which is for the time being under observation must be absolutely motionless. It is obviously impossible to ensure alternate periods of rest and motion with discs or other heavy pieces of revolving apparatus. The solution of this problem is the same as that which we adopted in chronophotography. The apparatus which is used for the analysis of movement is reversible, at least in

principle, and might be used for their synthetic reconstruction. Let us imagine that a strip of film has imprinted on it positive images, and that this strip is placed at the focus of the object-glass, and brightly illuminated from behind. If these figures are then projected on a screen as far removed from the object-glass as were the original objects, the figures will appear to actual scale.

Every time the objective is exposed by the rotation of the diaphragm an image is thrown on the screen, the outlines of which are perfectly defined, because the film is arrested by compression at the moment of exposure. As a matter of fact, it is better to adopt a special contrivance for projecting moving figures.

The following are the reasons which induced us to construct a new instrument, to which we have given the name, "Chronophotographic projector."

The Chronophotographic Projector.—In a projecting apparatus the exposure should be as long as possible, and the transparency should be arrested during the whole period of its projection upon the screen. These conditions must be fulfilled if bright and clear images are required. In the case of the analyzing apparatus, the exposures, on the contrary, should be as brief as the illumination will allow. For an insect's wing, the exposure should be no more than $\frac{1}{25000}$ part of a second. Now, with such a short exposure, an image would be almost invisible if greatly enlarged by projection; and this would still be the case even were the source of illumination very powerful. The most important point in constructing a projector is to secure as long an exposure as is possible. For instance, if ten images were taken per second, the exposure should be half or a third as long; that is to say, for $\frac{1}{20}$ or $\frac{1}{30}$ of a second, instead of for $\frac{1}{1000}$ of a second, which is the usual exposure allowed by

an analyzing apparatus. Instead of the small fenestrations on the circular diaphragms, long slits should be made, occupying a third of their circumference. During this long exposure, the film should be completely arrested, and for this purpose the compressor should have a particular kind of cam.

To realize the nature of a movement satisfactorily, it is as well to reproduce it several times. This may easily be done by an apparatus fitted with revolving discs; but, as in our apparatus, we have to use a length of film, it should be glued together at the ends, so as to produce an endless series of images continually rotating at the focus of the objective. Such a strip as this could not be introduced into the ordinary chronophotographic apparatus.

We have therefore constructed a special apparatus, in which an endless length of film containing forty or sixty figures, or even more, is allowed to pass without cessation under the field of the objective.

The illumination, which is from behind, and consists either of the electric light or the sun itself, projects these figures upon a screen. This instrument produces very bright images, but it is noisy, and the projected figures do not appear as absolutely motionless as one could wish.

Having arrived at this point in our researches, we learned that our mechanic had discovered an immediate solution of this problem, and by quite a different method; we shall therefore desist from our present account pending further investigations.

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THE END.

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